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Rapid and low-cost fabrication technique for tilted microlens array

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Abstract

In this study, the tilted microlens array was manufactured using oblique exposure and incomplete thermal reflow. The oblique exposure was used to generate an inclined photoresist column array with a round section on the wafer. When the temperature of superficial photoresist reaches the glass transition temperature during the thermal reflow process, the tilted microlens structure can be formed by controlling the thermal reflow time. The results showed that the inclined angles of photoresist columns were very close to the oblique exposure angles. Therefore, the inclined photoresist column with a specified angle can be manufactured accurately through this process. During the incomplete thermal reflow process, the thermal reflow time is a very important experimental parameter. The experiment results showed that when the thermal reflow time was less than 3 minutes, the superficial photoresist in glass state couldn’t be completely converted into rubber state thus a microlens couldn’t be shaped. Although microlens morphology on part of its structure was formed, its top of structure was still flat. In order to obtain the best shape of microlens, the thermal reflow time must be properly controlled based on different diameters of photoresist column. However, if the thermal reflow time was over 4 minutes, the glass state would gradually disappear at base part of inclined photoresist column, the base part of inclined photoresist column lost the ability of dominating the tilted angle of microlens which tended to become smaller and smaller. When all the photoresist were converted into the rubber state, the tilted angle of microlens would change no more. With proper control of the thermal reflow temperature and time, the microlens arrays with the tilted angle larger than 60° can be fabricated by using the proposed method.

Keywords: Asymmetric microlens array, Oblique exposure, Incomplete thermal reflow.

1. Introduction

Reflective liquid-crystal displays, featured with thin volume and light weight owing to its simplified backlight module, now are widely applied to the personal digital assistant (PDA) and other mobile communication equipments, such as the polymer dispersed liquid crystal (PDLC) for mobile phones and cholesteric liquid crystal display (CLCD) for e-books. The purpose of applying microlens array to the optical elements is to improve the illuminating brightness and simplify the structure of light-guide module. The microlens shape is designed to enhance the effect of luminous flux so as to improve the light throughput of projector of thin film transistor liquid crystal display (TFT-LCD). It is shown on the notebook display that 25% light output can be enhanced when using the microlens (Ezell, B., 2001). The asymmetric microlens array can gather the ambient incident light from various angles and shift the vertical reflected light to the horizontal direction, so as to effectively reduce the glare effect caused by the surface reflection going into the visual angle. And it also deflects the ambient inclined incident light toward the visible direction, distributing most reflected light in sight (Ko, F. J. & Shieh H. P. D., 2000), so as to enhance the brightness, contrast ratio, visual angle and uniformity of images reflected by the display, greatly improve the readability of reflective liquid crystal display and increase its applications, thus the efficiency or resolution of light source in the future can be increased.

If the outside light shines on the unprocessed flat surface, the light reflected into eyes from certain angles will make people feel dizzy and thus they cannot read the contents on the screen clearly. For example, people always cannot read the texts when using mobile phones in the sun, which is caused by the “glare”. An anti-glare film is designed to cut down on the amount of light that reflects off the display. Reflected light or glare can be very fatiguing to the eyes and reduces the contrast, colors and sharpness of the display. An anti-glare film makes viewing a display more pleasant for most people, and reduces eyestrain. Most LCD monitors have an anti-glare film with microlens array on the reflecting surface to scatter the light, rather than allowing it to reflect off a smooth surface. Huang et al (2002) developed the multi-asymmetric microlens array light control film, which can effectively enhance the image brightness and quality of the colorful reflective liquid-crystal display. It successfully decreases the reflected light from the mirror reflection angle of 30° to the angle of 14° and realizes the anti-glare effect. Lin et al (2008) proposed an asymmetric microlens array with long and short axises to change the vertical and horizontal light emitting angles. Based on the stimulated and experimental results, the horizontal light emitting angle can be increased to 31° and the vertical one can be reduced to 13° by using the bidirectional asymmetric microlens array with high fill factor as the optical scattering film, and the optical uniformity can be effectively enhanced.

The production of microlens array can adopt various methods such as E-beam lithography, lithography and etching, hot pressing (Yang, H., Chou, M.C., Yang, A., Mu, C.K. & Shyu, R.F., 1999) and thermal reflow (Yang, H., Pan, C. T. & Chou, M. C., 2001). Base on the principle of photoresist column melting on a substrate (Daly, D., Steven, R. F., Hutley, M. C. & Davies, N., 1990), thermal reflow technology is usually adopted to manufacture the refractive microlens array. When the heating temperature reaches the glass transition temperature of photoresist, the photoresist will be melted into liquid state. Since the surface tension effect leads to a hemisphere liquid photoresist on the substrate, microlens with various focal lengths can be produced by adjusting the contact angle between photoresist and surface of substrate. Lin et al (2003) and Yang et al (2004) proposed a special process, in which the quadrilateral and hexagonal microlens arrays with nearly 100% fill factor were produced by adopting the incomplete thermal reflow technology. Schilling et al (2000) analyzed the effects of gravity and surface tension of liquid photoresist on the shape of microlens in thermal reflow by the finite element method, and discussed that the lens shape may be affected by the hydrophobicity and hydrophilicity of substrate. They found it was available for microlens to avoid sagging in thermal reflow by the gravity effect when inverting the substrate. A smaller contact angle can be obtained to make the focal length longer by manufacturing the microlens mold with the photoresist. This method is suitable to manufacture a lens with large numerical aperture. The advantages of thermal reflow technology include low material and equipment costs, simple technology and easy control.

Furmidge et al (1962) found that the drop slippage on the inclined plane was related to the factors like drop weight, inclined angle and surface tension. The drop volume of critical slip can be derived from their research, and the result showed that the theoretical values were in good agreement with the experimental ones. ElSherbini et al (2004) discovered from the experiments that, when the Bond Number is equal to zero (i.e. without inclined angle), the contact surface between drop and substrate is circular; when the inclined angle is larger than zero, it is elliptical, and when the drop slips, it is egg shaped. Bateni et al (2005) found that, in addition to the effects of gravity and surface tension, the extra electrical field can also change the drop shape. When the extra electrical field from anti-gravity direction is large enough, the gravity influence can be neglected. The drop shape changes significantly while 9V electrical field is enforced. It can be applied to such aspects as inkjet, electrowetting technology, liquid physical separation or alloy manufacturing technology in stimulated weightlessness in space.

In order to use the refractive liquid crystal display in different circumstances more widely, it is necessary to develop a way to produce appropriate and reliable light control film rapidly and effectively. This research developed the tilted microlens array using oblique exposure and incomplete thermal reflow process. A schematic diagram of tilted microlens manufactured with proposed method is shown in Fig. 1. After the photoresist coating process, oblique exposure should be conducted through mask alignment. And after development, the inclined photoresist column on the base can be obtained. During the incomplete thermal reflow process, the unmelted base can precisely define the bottom of the liquid photoresist as a round shape. Electroforming technology is then used to convert the photoresist patterns into a metallic mold for polydimethylsiloxane (PDMS) tilted microlens. Due to the technique developed, it is suitable for the mass production of tilted microlenses.

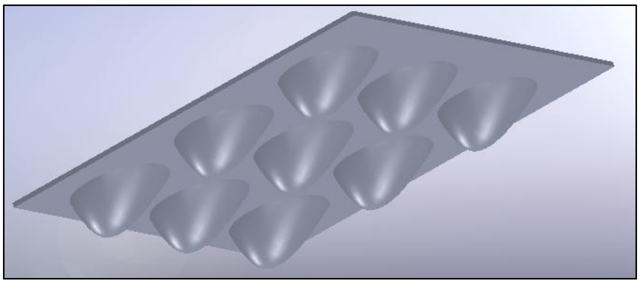


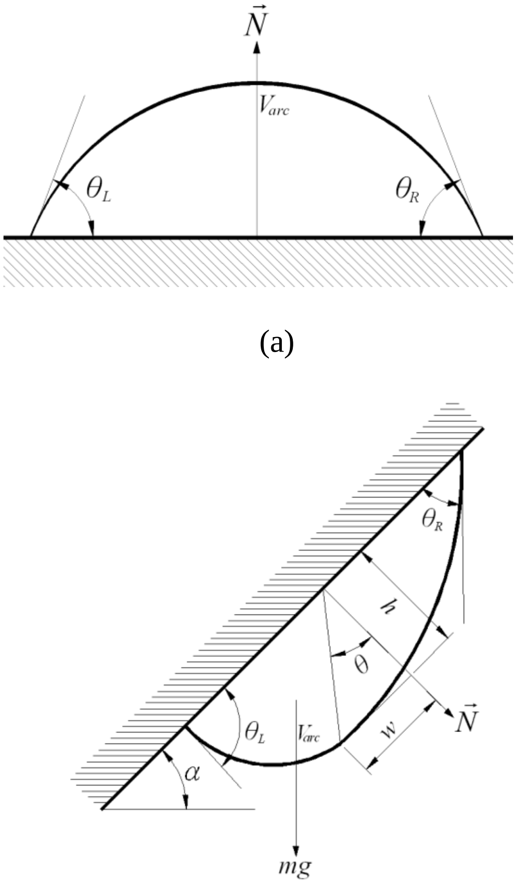
Fig. 1 A schematic diagram of tilted microlens manufactured with proposed method.

2. Fabrication methods

In general microlens with spherical surface, the normal direction of substrate from the center of bottom will pass through the arc vertex V_{arc}, and its contact angles θ_L and θ_R at both sides will be equal and form a symmetric spherical lens as shown in Fig. 2(a). However, in the tilted lens, its normal direction from the center of bottom won't pass through the arc vertex and there is an offset distance w from the arc vertex to the normal of the bottom center. Therefore, the contact angles θ_L and θ_R at both sides will be different, as shown in Fig. 2(b). The tilted angle is defined as following equation

$$\theta = \tan^{-1}\left(\frac{w}{h}\right) \tag{1}$$

Wherein, h represents the height from bottom to the arc vertex.

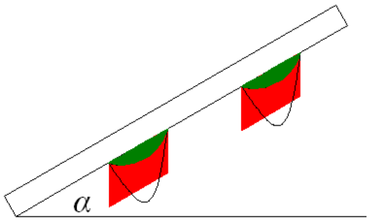


(a)

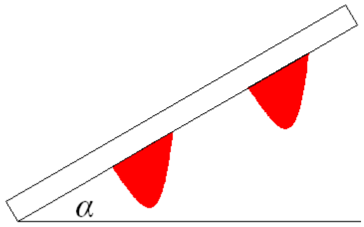
(b)

Fig. 2 Geometric schematic diagram of tilted microlens: (a) Definition of tilted microlens; (b) Geometric drawing of tilted microlens.

Due to the surface tension, only the symmetric microlens in spherical cap shape can be produced by the traditional thermal reflow method. In this paper, the microlens array was manufactured in incomplete thermal reflow by controlling the oblique exposure angle, temperature and time of thermal reflow. The oblique exposure was used to generate an inclined photoresist column array with a round section on the wafer and then the wafer was inverted and inclined on the fixture, so as to produce the tilted microlens array by adopting the incomplete thermal reflow and gravity effect, the manufacturing process is shown in Fig. 3. In this experiment, a silicon wafer was used as the substrate. The wafer was cleaned and dehumidified in an oven at a temperature of 150 °C for 30 minutes. To increase the adhesive force between the photoresist and substrate, the substrate was coated first with a thin layer of Hexamethyldisilazane (HMDS) and then coated with a layer of positive photoresist (AZ4620) using a spin coater. The spin coating revolution speed can be used to control the photoresist thickness and the spin coating lasts about 20 seconds. To prevent the mask from sticking onto the photoresist surface when exposed, the photoresist was then prebaked in a convection oven at 90 °C for 3 minutes. This removes the excess solvent from the photoresist and produces a slightly hardened photoresist surface. The substrate coated with AZ4620 photoresist was tilted at a certain angle.



(a)



(b)

Fig. 3. Schematic diagram of oblique exposure and incomplete thermal reflow process: (a) Incomplete thermal reflow process; (b) Microlens is formed after incomplete thermal reflow.

The sample was exposed for 20 seconds through the mask using a UV mask aligner (EVG620). This aligner has soft, hard contact or proximity exposure modes at a NUV (near ultra-violet) wavelength of 350-450nm and lamp power in the 200-500W range. Through development, a inclined photoresist column can be formed on the silicon substrate. Then the sample was placed inside a vacuum baker for the incomplete thermal reflow process. During the incomplete thermal reflow, the superficial photoresist in Fig. 3(a) was converted into rubber state by controlling the thermal reflow time, and then the lens shape can be formed under surface tension and gravity effect. Since the bottom of inclined photoresist column hasn’t reached the glass transition temperature, it is still in glass state. Therefore, the original inclined angle can be maintained, as shown in Fig. 3(b). The bottom shape of the liquid photoresist is restricted by the round base, photoresist mold of tilted microlens might be produced under gravity by inverting and tilting the substrate.

3. Results and discussion

An Optical microscopy(OM) photograph of the inclined photoresist column for oblique exposure angle of 45° is shown in Fig. 4. Its inclined angle of photoresist column is about 46°, which is very close to the oblique exposure angle. The tilted microlens is finished by inclined photoresist column using incomplete thermal reflow method. When the temperature of superficial photoresist reaches glass transition temperature, the tilted microlens structure can be formed after the superficial photoresist is in rubber state by controlling the thermal reflow time.

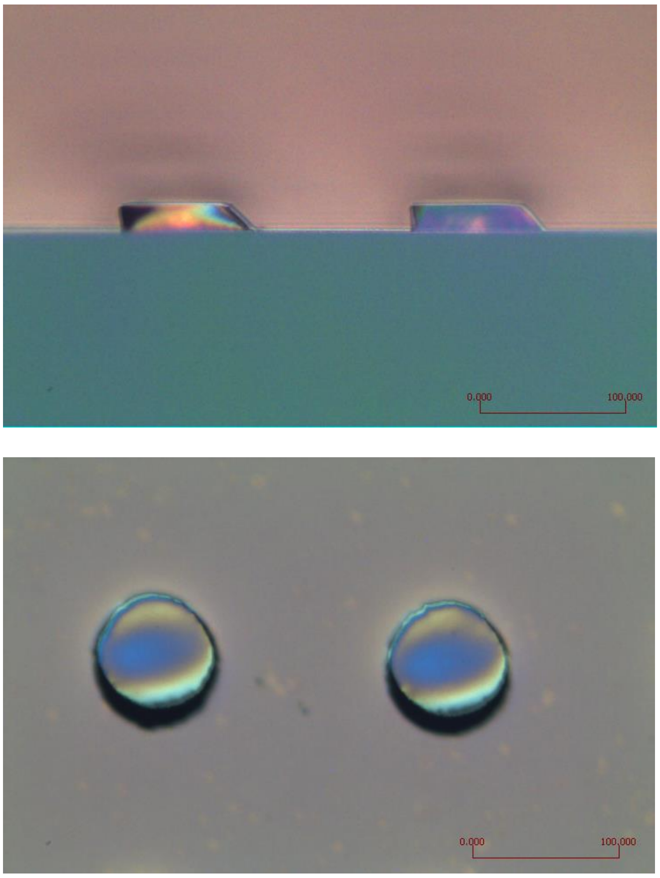
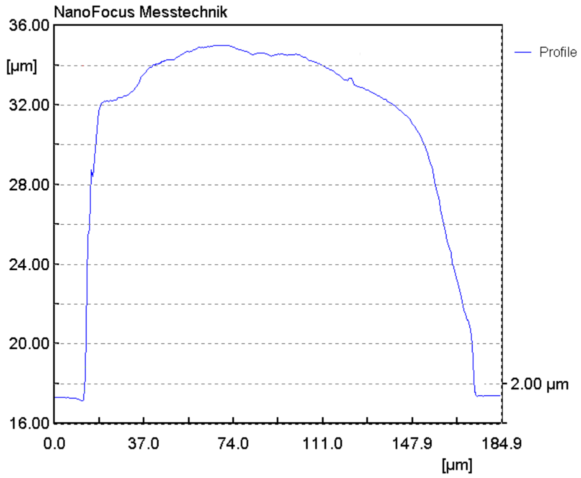
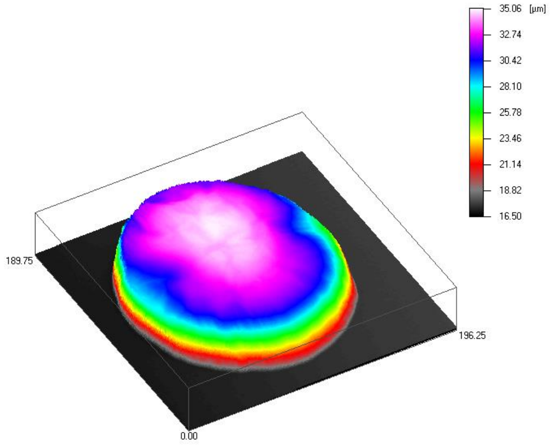


Fig. 4. The OM photograph of the inclined photoresist column for oblique exposure angle of 45°.



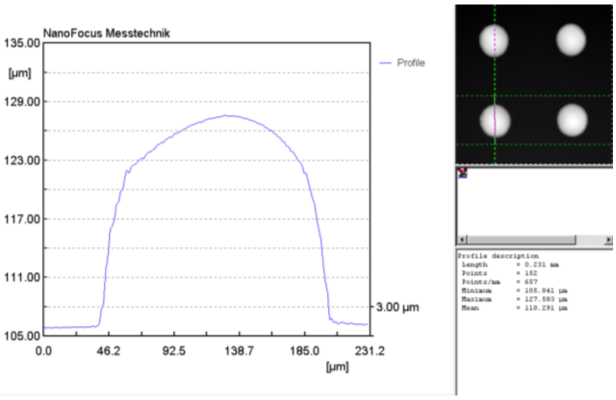
(a)



(b)

Fig. 5. (a) The cross-sectional profile; (b) The 3D surface profile for tilted microlens, when the thermal reflow time was less than 3 minutes.

During the incomplete thermal reflow process, the thermal reflow time is a very important experimental parameter. The experiments were conducted at the time interval of 30 seconds, the incline angle of photoresist column with a diameter of 80 µm was 60°. The experiment results showed that when the thermal reflow time was less than 3 minutes, the superficial photoresist in glass state couldn't be completely converted into rubber state thus a microlens couldn't be shaped, whose surface topography is shown in Fig. 5. Although microlens morphology on part of its structure was formed, its top of structure was still flat. In order to obtain the best shape of microlens, the thermal reflow time must be properly controlled based on different diameters of photoresist column. According to the experiments, the tilted angle of 60° can be achieved when the thermal reflow time lasts for 3 minutes and 30 seconds. However, if the thermal reflow time was over 4 minutes, the glass state will gradually disappear at base part of inclined photoresist column, the base part of inclined photoresist column lost the ability of dominating the tilted angle of lens which tended to become smaller and smaller, as shown in Fig. 6(a). When all the photoresist were converted into the rubber state, the tilted angle of microlens would change no more and be fixed at about 22° calculated by equation (1) with a height of 22 µm and an offset distance of 9 µm, and its surface topography is shown in Fig. 6(b). The results were almost the same as those obtained at various inclined exposure angle, for they were caused by the gravity effect and surface tension. The results show that microlens array with a bigger tilted angle can be manufactured by controlling thermal reflow time properly. In order to obtain the expected tilted angle, it is necessary to control the thermal reflow time appropriately according to different photoresist volumes. The relationship between time of thermal reflow and diameter of inclined photoresist column is shown in Fig. 7.



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Profile description
 Length       = 0.231 mm
 Points       = 152
 Points/mm    = 657
 Minimum      = 105.041 µm
 Maximum      = 127.583 µm
 Mean         = 110.291 µm
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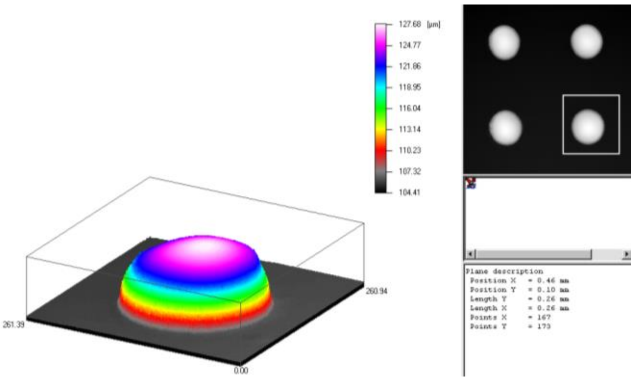
(a)



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Plane description
 Position X   = 0.46 mm
 Position Y   = 0.10 mm
 Length Y     = 0.26 mm
 Length X     = 0.26 mm
 Points X     = 167
 Points Y     = 173
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(b)

Fig. 6. (a) The cross-sectional profile with a height of 22 µm and an offset distance of 9 µm; (b)

The 3D surface profile for tilted microlens with 22° tilted angle, when the thermal reflow time was over 4 minutes.

As shown in Fig. 8, curve (1) represents the inclined angles of photoresist columns are very close to the oblique exposure angles. Therefore, the inclined photoresist column with a specified angle indeed can be manufactured accurately through this process. The tilted angle of microlens can be also controlled by the oblique exposure angle. The tilted angle of microlens is proportional to oblique exposure angle to the second power. For example, when the oblique exposure angle is 60°, the microlens with a 60° tilted angle can be manufactured, as shown in curve(2). An optical microscopy(OM) photograph of the tilted microlens using the proposed method is shown in Fig. 9. Fig. 10 shows the corresponding cross-sectional profile of a tilted microlens with 60° tilted angle measured using an optical non-contact surface profiler NanoFocus μScan 3-D laser profilometer.

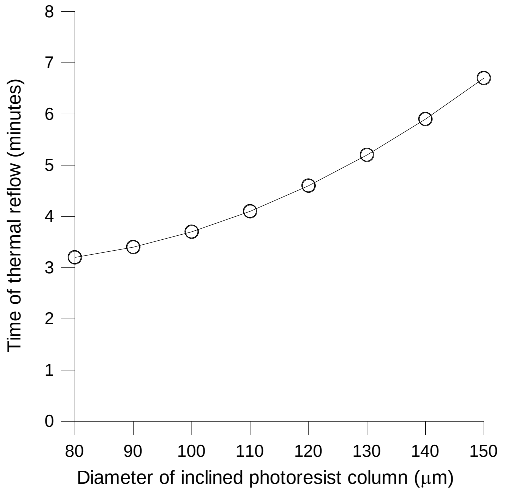


Fig. 7. The relationship between time of thermal reflow and diameter of inclined photoresist column.

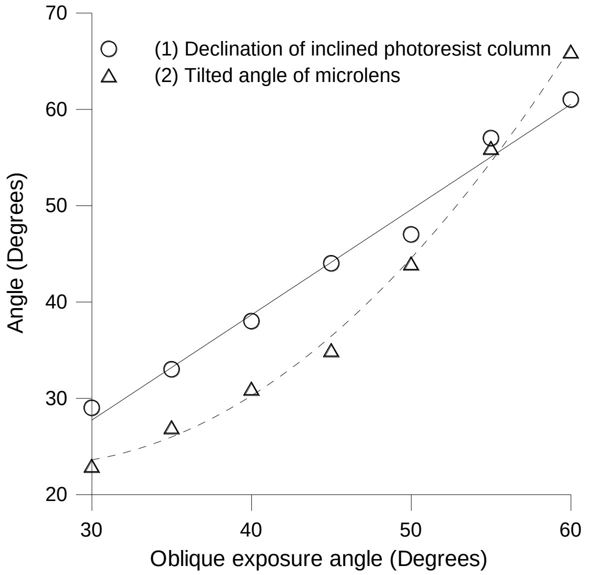


Fig. 8. The variation in declination of inclined photoresist column and tilted angle of microlens for various oblique exposure angles.

After the tilted microlens prototype was finished, the next step was to transfer the tilted microlens array into a metallic mold using an electroforming technique for the molding process. The concave electroforming mold was used to fabricate PDMS tilted microlens. The PDMS tilted microlens wa cured in a vacuum oven for 2 hours at 5 mTorr of pressure and 75 ℃. The PDMS tilted microlens was then peeled off from the metallic mold. The surface roughness of PDMS tilted microlens array was determined using an atomic force microscope (AFM). The measured size was 5×5 μm^2 on the top surface of PDMS tilted microlens. It shows the average microlens surface roughness (Ra) was 2.61 nm as shown in Fig. 11. It reveals that the proposed fabrication method for the tilted microlens has been proven acceptable.

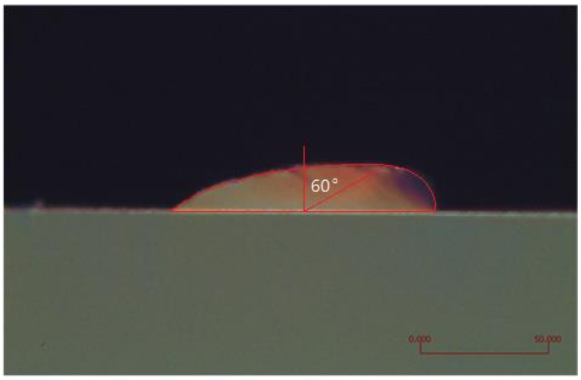


Fig. 9. The OM photograph of tilted microlens fabricated using the proposed method.

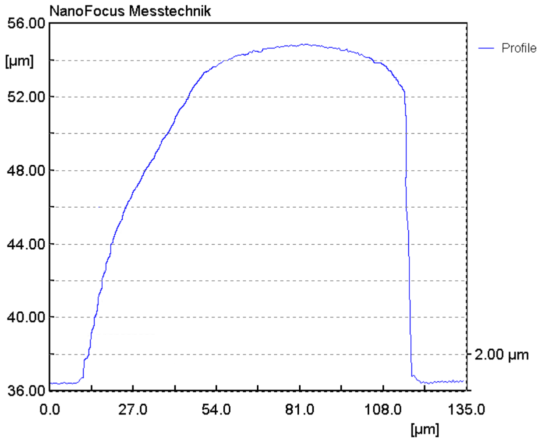
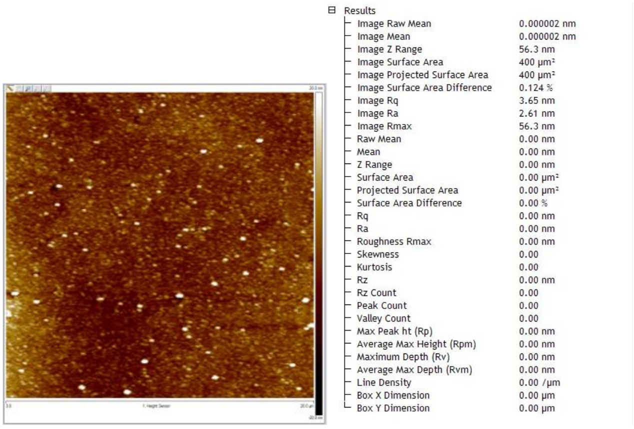


Fig. 10. The cross-sectional profile for tilted microlens with 60° tilted angle.



Results

Image Raw Mean	0.000002 nm
Image Mean	0.000002 nm
Image Z Range	56.3 nm
Image Surface Area	400 µm²
Image Projected Surface Area	400 µm²
Image Surface Area Difference	0.124 %
Image Rq	3.65 nm
Image Ra	2.61 nm
Image Rmax	56.3 nm
Raw Mean	0.00 nm
Mean	0.00 nm
Z Range	0.00 nm
Surface Area	0.00 µm²
Projected Surface Area	0.00 µm²
Surface Area Difference	0.00 %
Rq	0.00 nm
Ra	0.00 nm
Roughness Rmax	0.00 nm
Skewness	0.00
Kurtosis	0.00
Rz	0.00 nm
Rz Count	0.00
Peak Count	0.00
Valley Count	0.00
Max Peak ht (Rp)	0.00 nm
Average Max Height (Rpm)	0.00 nm
Maximum Depth (Rv)	0.00 nm
Average Max Depth (Rvm)	0.00 nm
Line Density	0.00 /µm
Box X Dimension	0.00 µm
Box Y Dimension	0.00 µm

Fig. 11. AFM image of surface morphology for tilted microlens.

4. Conclusion

In this study, a new fabrication method of tilted microlens array for light control films was developed to increase the efficiency of a liquid crystal display that can collect lateral light sources and improve the dazzling problem within the angle of view. The inclined photoresist columns with a round cross-section were successfully manufactured by the oblique exposure. The experimental results showed that the oblique exposure from different angles can precisely control the declination of the inclined photoresist column. During the incomplete thermal reflow processing, only the surface part of photoresist column reaches the glass transition temperature, which is transformed from a glassy state into a rubbery state. In order to minimize the structural surface energy and reduce the surface area, the surface of the inclined photoresist column forms the shape of a microlens. With proper control of the thermal reflow temperature and time, the photoresist at the base will still maintain the original inclination and glassy state because it hasn’t reached the glass transition temperature. When the thermal reflow time is not enough, the microlens shape cannot be formed due to the insufficient superficial photoresist in rubber state. The thermal reflow time of 3 minutes and 30 seconds can produce the best microlens shape with a tilted angle of 60°. Over 4 minutes, most of the oblique photoresist will be converted into rubber state because of long thermal reflow time. Thus the glass state of photoresist in base disappears gradually so as to losing the ability of dominating the inclined angle and the tilted angle tends to be smaller and smaller. In order to obtain the expected tilted angle, it is necessary to control the thermal reflow time appropriately according to different photoresist volumes. The experimental results showed that the oblique exposure from various angles can precisely control the tilted angle of the microlens array. The microlens arrays with the tilted angle larger than 60° can be fabricated by using the proposed method.

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快速低成本傾斜微透鏡陣列創新製程

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摘　要

本研究開發出一種應用於光控膜上的斜透鏡陣列製程，透過該斜透鏡可以增進液晶顯示器收集側向光源效率並改善視角內所產生的眩光問題。本研究先透過微影製程技術來製作具圓形截面的斜向光阻柱陣列，利用在曝光時將塗有光阻的基板放置於有一傾斜角度的治具上進行曝光，在不完全熱熔製程中，光阻柱透過光阻表面部分升溫達到玻璃轉化溫度，使其由玻璃態轉變為橡膠態，光阻柱為了要降低結構的表面能，進而使表面積最小化，因此斜向光阻柱表面部分形成透鏡形狀，在熱熔溫度與時間控制適當的情況下，基地部分光阻溫度則因為尚未達到玻璃轉化溫度，仍維持原有之傾斜角度，實驗結果顯示透過不同角度的斜向曝光可以控制斜向光阻柱陣列的傾斜角度，再使用倒置光阻基板之不完全熱熔方式，適當地控制熱熔時間可製作出偏斜角 60˚以上的斜透鏡陣列。

關鍵詞：非對稱微透鏡、光控膜、不完全顯影熱熔製程