Journal of Nan Kai, Vol. 15, No. 1, pp.13-21 (2018)

Facile and reliable method for fabricating tilted microlens array

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投稿日期：2018 年 1 月
接受日期：2018 年 6 月

Abstract

A new manufacturing method for an asymmetric microlens array for a light control film has been developed to improve the efficiency of a dazzling liquid crystal display that can collect a lateral light source and improve the viewing angle. During the conventional heat reflow without the substrate, an asymmetric microlens may be produced by the tilting substrate under gravity. However, the bottom shape of the lens will become elliptical and the higher diameter ratio of the photoresist column will cause the lens to slide. Prior to the thermal reflow process, a stripping method was used to form the round bottom. After the wafer is tilted, the base can not only limit the bottom shape of the liquid photoresist to a circular shape, but also prevent the sliding of the liquid photoresist during the heat reflow process. Compared with the base, the concave base is relatively reliable, effectively avoid the lens sliding. The proposed manufacturing method facilitates mass production to achieve a high yield asymmetric microlens suitable for use in light control films which can improve the brightness and contrast of the reflective liquid crystal display.

Keywords: Asymmetric microlens, Light control film, Lift-off

1. Introduction

Over the past few years, the main microlens array applications have increased the illumination brightness and simplified the construction of the light guide module. In the notebook computer display, the use of microlens technology, the light output increased by 25% (Ezell, 1991). The integrated microlens array is a very important part of the CCD, auto focus module, copier (Smith, 1989) and fiber optic interconnect (Leggatt & Hutley, 1991). Khizar, Fan, Kim, Lin, & Jiang, (2005) found that under the 20mA DC drive, the microlens array was formed to enhance the output power of the UV LED (UV light emitting diode) by 55%. The light source must be brighter and more durable, while reducing device power consumption, size and weight. In the micro-electromechanical (MEM) technology in parallel development, low-light technology is also developing rapidly. With this advanced technology, miniature patterns can be replicated to form high-quality, low-cost optics (Veldkamp, 2005). In order to improve production efficiency, several replication methods have been used for the manufacture of plastic microlens arrays, including injection molding, hot embossing (Yang, Chou, Yang, Mu, & Shyu, 1999; Yang, Pan, & Chou, 2001) and extrusion embossing (Jiang, Huang, Ciou, Chang, & Yang, 2007). The oblique microstructure was fabricated using UV (UV) lithography (Yu, Li, & Zhang, 2006; Sato, Yagyu, Ito,& Shoji, 2006). The advantage of UV lithography is that it allows batch manufacturing, low cost, high uniformity and small size. The described oblique UV exposure method is useful for the manufacture of 3D structures. Using this micro-manufacturing method, a tilting plate is constructed to control the exposure and to control the refraction angle of the light.

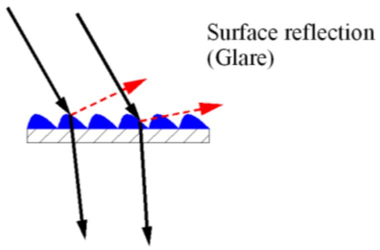


Fig. 1 Diagram that asymmetric microlens array removes dazzling light and increases brightness of incident light and move inclined incident light to approximately forward direction to make most refracted light distributed in observing view angle.

As shown in Fig. 1, Asymmetric microlens array can collect environmental incident lights from multiple angles and move original vertical specular reflection light to horizontal direction, to reduce proportion of dazzling light due to specular reflection effectively and move inclined incident light to approximately forward direction, to make most refracted light distributed in observing view angle, so as to improve brightness, contrast, view and uniformity of the display. It can greatly improve readability of LCD and increase application scope, expecting to improve efficiency of light source or resolution. Hung *et al* (2012) proposed an asymmetric microlens array made through off-axis optical lithography manufacture procedure. They used two circular photomasks with different diameters to conduct two exposure processes. In the first exposure, they used the lift-off method to get an off-axis circular metal base. In the second exposure, they used the alignment exposure method to form a photoresist column on the off-axis circular metal base. In thermal reflow, the off-axis metal base could pull the lentoid liquid photoresist vertex to side due to influence of surface tension, and formed an inclined microlens after solidification. The asymmetric microlens array could improve efficiency of the LCD in collecting side light source and solve the problems of dazzling light in view angle. Lin, *et al* (2012); Lin *et al* (2015) utilize inclined exposure to make the inclined photoresist array have circular section. In incomplete thermal reflow, local temperature rise on surface of photoresist column reaches glass transition temperature, to transform glass state into rubber state, thus part of inclined photoresist column surface forms lens shape. Under proper control of thermal reflow temperature and time, some photoresist temperature still has original inclined angle for not reaching glass transition temperature, which can be made to inclined lens array with declination angle of more than 45°. Hung, Chang, Shen, & Yang (2014) used two photoresists with different melting temperatures to fabricate the tilted microlens. AZ-5214E (glass transition temperature is higher than 180°) is the first lower layer of photoresist, thickness is 5 m, and AZ-4620(glass transition temperature is higher than 125℃) is the second upper layer of photoresist. Only one lithography process can get double-layer heterogeneous photoresist column. Finally, utilize inverse inclined thermal reflow method to fabricate the tilted microlens at 150℃. In thermal reflow, glass transition temperature of AZ-5214E is higher than 150℃, thus it will not become liquid and be able to act as foundation support of AZ-4620 in thermal reflow. The asymmetric microlens array can be made by AZ-4620 after thermal reflow. Hung, Hung & Shen (2015) used magnetic forces to change the deflection angle of the photoresist droplets. The nanometer magnetic powder is uniformly added to the photoresist, and a magnetic field is suitably applied in the heat return to tilt the photoresist droplets toward the magnetic field, thereby producing an asymmetric microlens array. Then, the magnetic field is changed to control the inclination angle of the tilt lens to avoid the drawbacks of the tilt lens due to the inversion of the wafer, which can greatly improve the stability of the manufacturing process.

In order to make reflection type LCD applied in different places widely, a manufacture process of asymmetric microlens array is developed to produce proper and reliable light control film quickly and directly. This research fabricates the asymmetric microlens array using lift-off method and thermal reflow with an oblique substrate. In this work, a convex or concave circular substrate is formed on the wafer by using a stripping process. After the photoresist coating process, exposure should be done by mask alignment. After development, a circular photoresist column on the substrate can be obtained. In the heat reflow process, as shown in Fig. 2, a photoresist mold of an asymmetric microlens can be produced by the tilting substrate under gravity. The substrate can not only limit the bottom shape of the liquid photoresist to a circular shape, but also prevent the sliding of the liquid photoresist. The photoresist pattern is then converted into a metal mold for a polydimethylsiloxane (PDMS) asymmetric microlens array using electroforming techniques. Due to the development of the technology, it is suitable for large scale production of asymmetric microlens arrays.

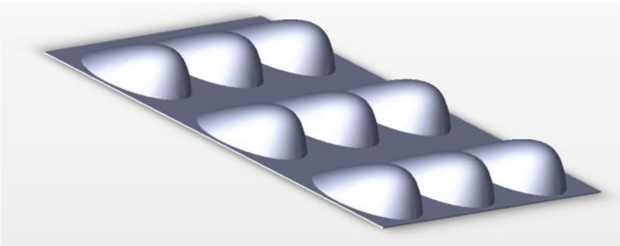


Fig. 2 During the thermal reflow process, photoresist mold of asymmetric microlens might be produced under gravity effect by tilting the substrate.

2. Fabrication methods

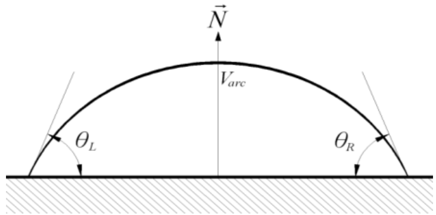
Furmidge (1962) found that the sloping plane on the fall and fall weight, tilt angle and surface tension and other factors. The decrease in critical slip can be derived from their studies, and the results show that the theoretical values are in good agreement with the experimental values. ElSherbini & Jacobi (2004) found that when Bond Number is equal to zero (ie, without tilt angle), the contact surface between the droplet and the substrate is circular; when the tilt angle is greater than zero, it is elliptical , When it falls, it is egg-shaped. Bateni, Ababneh, & Elliott (2005) found that in addition to the effects of gravity and surface tension, additional electric fields can also change the shape of the droplet. When the extra electric field in the anti-gravity direction is large enough, the influence of gravity can be ignored. When the 9KV electric field is forced, the droplet shape changes significantly. It can be used in space simulation of weightlessness of the inkjet, electric wetting technology, liquid physical separation or alloy manufacturing technology and so on.

In general microlens with spherical surface, the normal direction $\vec{N}$ 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. 3(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. 3(b). The tilted angle is defined as following equation

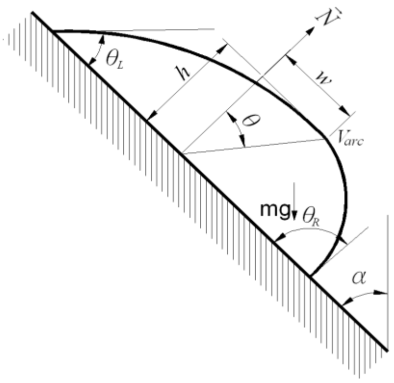
$$\theta = \tan^{-1}\left(\frac{w}{h}\right) \tag{1}$$

Wherein, h represents the height to the arc vertex.

In this work, a convex or concave circular substrate is formed on the wafer by using a stripping process. The round bottom can change the contact area between the liquid photoresist and the substrate and the contact pattern, thereby changing the surface tension of the liquid photoresist accordingly. And the bottom shape of the liquid photoresist may also be precisely defined as a circular shape and the sliding of the liquid photoresist may be prevented when the wafer is placed obliquely during the hot reflux process.



(a)



(b)

Fig. 3 (a) a geometric representation of a lens manufactured by conventional heat reflow (b) a geometrical representation of a tilt lens made by heat back and tilted substrates.

2.1. Convex round base

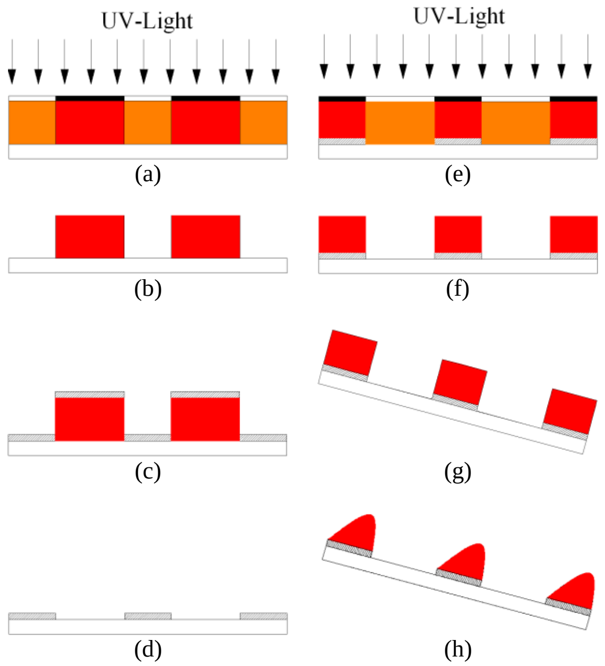
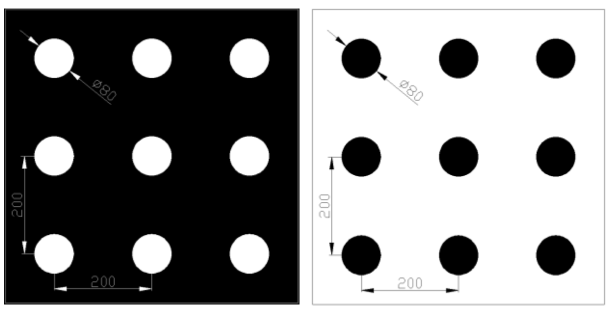


Fig. 4 (a) performing a first exposure by using a mask as shown in Fig. 5 (a); (b) after exposure, with a mask (c) copper sputtering; (d) removing the photoresist structure with acetone to retain the convex circular copper substrate; (e) coating the photoresist on the silicon substrate with a photoresist (f) forming a circular photoresist column on the copper base after development; (g) heat reflow with a tilted substrate; (h) forming a photoresist on the copper substrate; An asymmetric microlens photoresist mold was obtained by thermal reflow.

In this experiment, a silicon wafer is used as the substrate. The wafer is cleaned and dehumidified in an oven at a temperature of 150°C for 30 minutes. In order to increase the adhesion between the photoresist and the substrate, the substrate was first coated with a thin layer of hexamethyldisilazane (HMDS) and then coated with a layer of positive photoresist (AZ4620). The spin coating speed can be used to control the thickness of the photoresist and spin coater for about 20 seconds. To prevent the mask from adhering to the photoresist surface upon exposure, the photoresist was prebaked in a convection oven at 90 ℃ for 3 minutes. This removes excess solvent from the photoresist and produces a slightly hardened photoresist surface. As shown in Fig. 4 (a), first, exposure was performed on a photoresist coated with AZ4620 using a photolithography method and a mask shown in Fig. 5 (a). The round photoresist column was completed after immersion in the developer for 120 seconds and rinsed with deionized water. Thereafter, a photoresist (i.e., Fig. 4 (b)) patterned with the mask obtained by development was sputtered with a 6 m thick copper layer in vacuum sputtering (Fig. 4 (c)). The photoresist is then removed using acetone. The copper sputtered on the photoresist disappears (as shown in Fig. 4 (d)). By the above-mentioned treatment, a silicon substrate having a convex copper base can be obtained as shown in Figs. 6 and 7, which are spin-coated with a second photoresist. After the photoresist coating process, a second exposure should be made by mask alignment. The mask shown in Fig. 5 (b) is used for orientation exposure (as shown in Fig. 4 (e)). The sample was exposed to the mask for 20 seconds using a UV mask aligner (EVG620). The aligner has a soft, hard contact or proximity exposure mode at a lamp power of 350 to 450 nm at a NUV (near ultraviolet) wavelength and a power range of 200 to 500 W. Through the development, a circular photoresist column can be formed on the copper substrate (as shown in Fig. 4 (f)). The silicon substrate coated with the photoresist was placed in a vacuum oven for the hot reflux process. During the thermal reflow, the bottom shape of the liquid photoresist is restricted by the convex round copper base, photoresist mold of asymmetric microlens might be produced under gravity by tilting the substrate as shown in Figs. 4 (g) and (h).



(a) (b)

Fig. 5 Diagram of the geometrical dimensions of the mask. (Unit: μm)

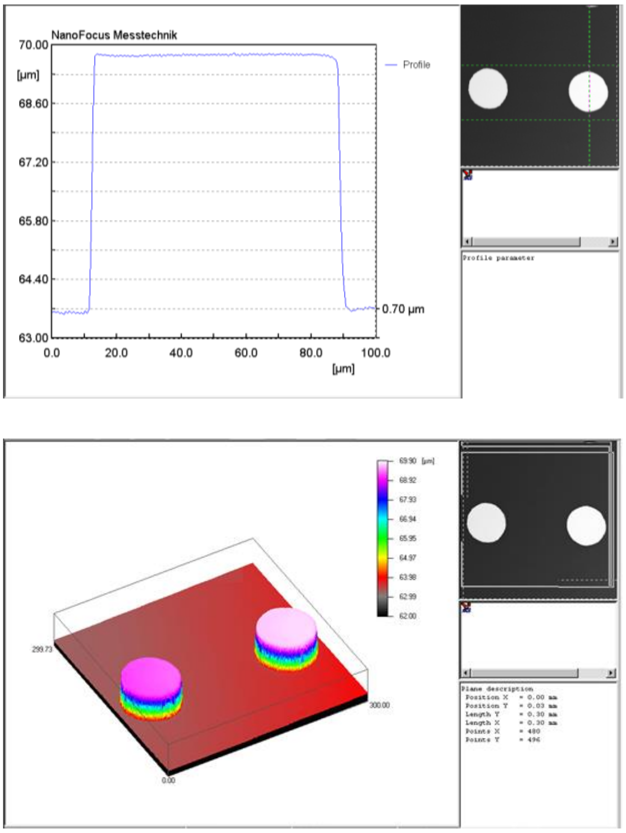


Fig. 6 (a) The cross-sectional profile and (b) the 3D surface profile for copper base.

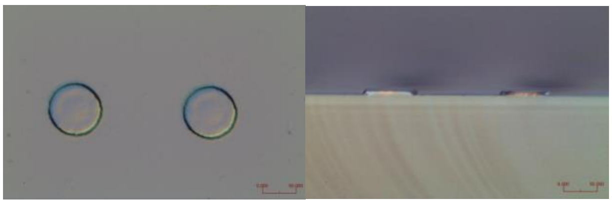


Fig. 7 The OM photograph of the copper base. (Unit: μm)

2.2. Concave round base

By using the mask shown in Fig. 5(b) during the first exposure, as described in Figs. 8(a) - (c), the copper film is complementary with the pattern of mask. In Fig. 8(d), concave round bases are formed and surrounded by the copper film. By using the original mask and conducting the alignment exposure on the photoresist coated with AZ4620 (as demonstrated in Fig. 8(e)), a round photoresist column on the concave round base can be obtained after development (shown in Fig. 8(f)). The silicon substrate coated with photoresist is placed inside a vacuum baker for the thermal reflow process. During the thermal reflow processing, photoresist columns reach a glass transition temperature (T_g), which is transformed from a glassy state into a rubbery state. Due to their high surface tension, the liquid photoresist tend to minimize the structural energy and reduce their surface trying to achieve a lens shape. And then the photoresist mold of asymmetric microlens can be obtained by tilting the substrate as shown in Figs. 8 (g) and (h). The same mask is used in the two exposure processes, along with high alignment accuracy. The experimental results prove that this method can achieve a high yield. Thus, this process is relatively reliable compared with the convex base.

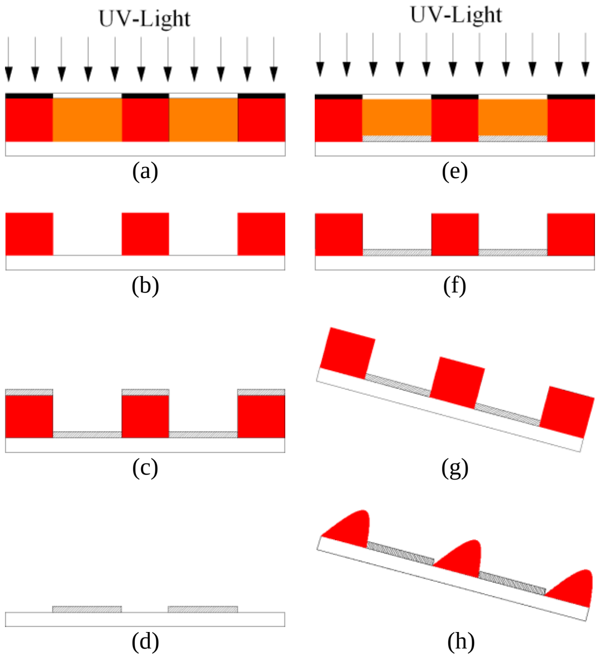


Fig. 8 A process for manufacturing an asymmetric microlens array by a concave substrate and a heat recovery method: (a) performing a first exposure by using a mask as shown in Fig. 5 (b); (b) after development, (c) copper sputtering; (d) removing the photoresist structure with acetone to form a concave substrate between the copper films; (e) coating the silicon substrate with a light- (f) obtaining an asymmetric microlens light by heat reflow; (g) obtaining an asymmetric microlens light by heat reflow; (h) forming an asymmetric microlens Engraving mold.

3. Results and discussion

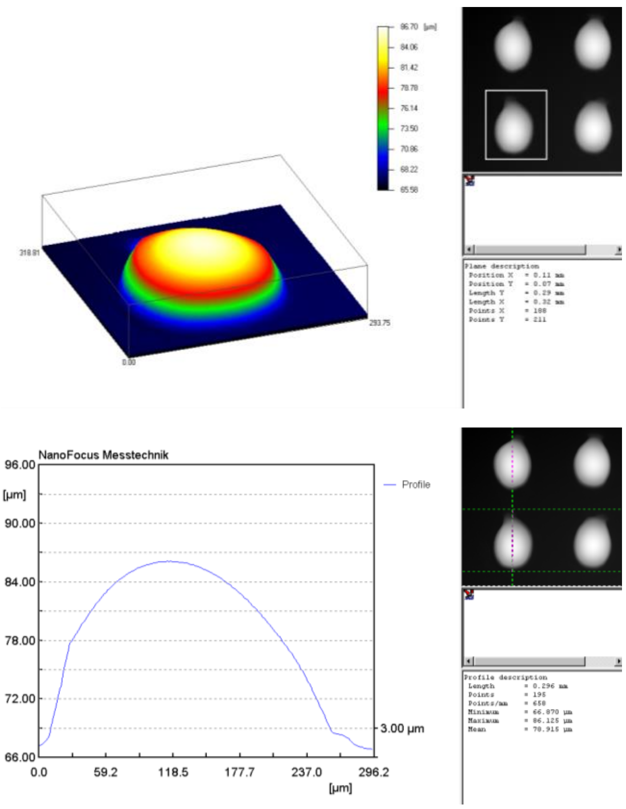


Fig. 9 (a) The bottom shape of asymmetric microlens is elliptical and (b) The lateral shape of asymmetric microlens is tilted under gravity by tilting the substrate during the traditional thermal reflow without base.

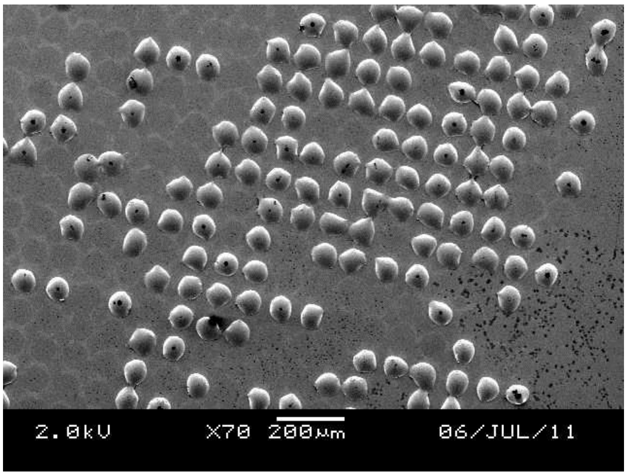


Fig. 10 The inclined angle of substrate exceeds the critical sliding angle, the sliding of lenses occurs.

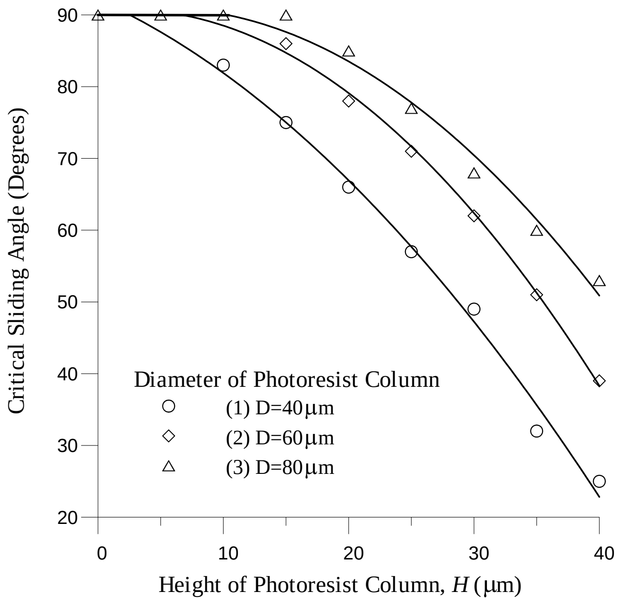


Fig. 11 During the traditional thermal reflow without base, the relationship between the critical sliding angle and height of photoresist column with various diameters.

In the absence of a conventional hot reflux of the base, an asymmetric microlens may be produced by gravity by tilting the substrate. However, as described by ElSherbini & Jacobi (2004), the 3-D surface profile of the asymmetric microlens of Fig. 9 is measured with an optical non-contact surface profile. The nano-focus µScan3-D laser describes its bottom shape to become elliptical. When the tilt angle of the substrate exceeds the critical slip angle, a lens slide may occur, and a scanning electron microscope (SEM) micrograph of an incomplete asymmetric microlens array is shown in Fig. 10. As shown in Fig. 11, when the height of the photoresist column remains the same, the smaller the diameter of the photoresist column, the smaller the contact area and the adhesion between the photoresist and the substrate, The smaller the critical slip angle of the resist microlens is. In addition, the experimental results show that when the diameters of the photoresist columns remain the same, the higher the photoresist column is, the higher the photoresist droplets are, and therefore easier to slide to obtain the microlens array.

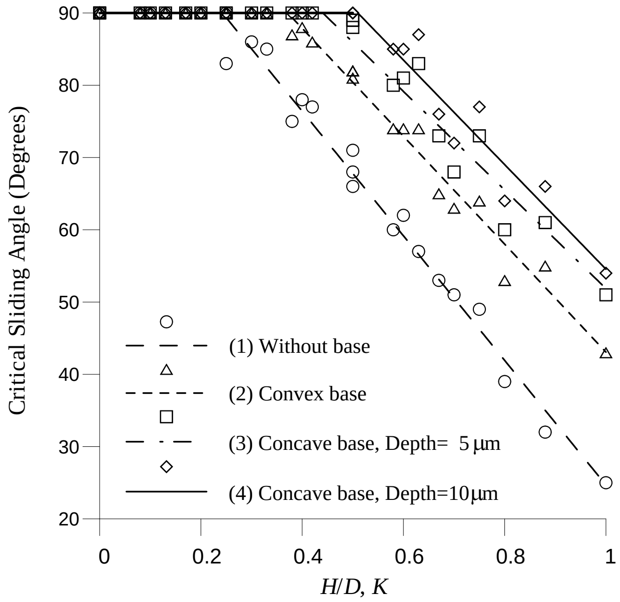
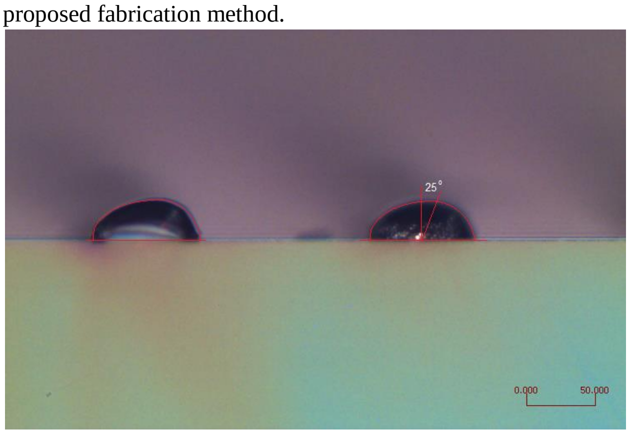


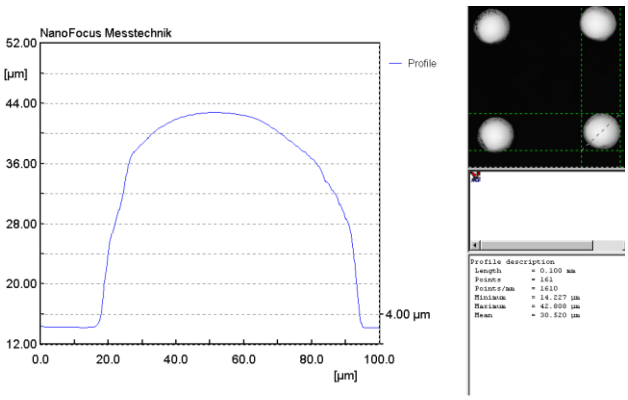
Fig. 12 The relationship between the critical sliding angle and height-diameter ratio of photoresist column.

If the horizontal axis of the coordinates in Fig. 12 is represented by the high diameter ratio (H / D, K) of the photoresist column, the relationship between the high diameter ratio and the critical slip angle may be linear. As shown in the curve (1) without the base, when the height-to-diameter ratio increases, the critical slip angle tends to decrease, but when K is less than 0.2, the photoresist of the microlens, even if the substrate is vertical (90 °) Not slipping). When the base is used to prevent the lens from sliding during heat return, the non-slip height diameter is increased to 0.4 as shown by curve (2) as KC. Curves (3) and (4) show that a higher non-slip height ratio can be achieved by using a recess. With the depth of the concave base, KC is getting bigger and bigger. For recesses with a depth of 10 microns, a non-slip height ratio of up to 0.5 can be achieved. Compared with the base, the concave base is relatively reliable, effectively avoid the lens sliding.

When D=80μm and H=30μm, the critical sliding angle is about 60° (conservative value) as shown in Fig. 11. After thermal reflow without a base, the tilted angle of fabricated microlens is only about 15°. From Fig. 12, the critical sliding angle can reach to 90°, thus the microlens with a tilted angle of 25° can be manufactured. The optical microscopy (OM) photograph and cross-sectional profile of the asymmetric microlens are shown in Fig. 13. After the asymmetric microlens prototype is finished, the next step is to transfer the asymmetric microlens array into a metallic mold using an electroforming technique for the molding process. The concave electroforming mold is used to fabricate PDMS asymmetric microlens. The PDMS asymmetric microlens is cured in a vacuum oven for 2 hours at 5 mTorr of pressure and 75℃. The PDMS asymmetric microlens is then peeled off from the metallic mold. The surface roughness of PDMS asymmetric microlens array was determined using an atomic force microscope (AFM). The measured size was 5×5 m^2 on the top surface of PDMS asymmetric microlens. It shows the average surface roughness (Ra) was less than 4 nm. It reveals that the surface roughness is acceptable for the asymmetric microlens fabricated using the proposed fabrication method.



(a)



(b)

Fig. 13 (a) The OM photograph and (b) The cross-sectional profile of PDMS asymmetric microlens array using the proposed fabrication method.

4. Conclusions

In this work, the stripping method is used to form a round bottom before the thermal reflow process. After the photolithography process, a photoresist column on the round bottom can be obtained. The experimental results show that the photoresist molds that produce asymmetric microlenses under gravity can be produced by tilting the substrate during the heat reflow process. The higher diameter ratio will cause the lens to slide when there is no heat return to the base, and the non-sliding height diameter is only about 0.2% higher than the KC. The convex base not only limits the bottom shape of the liquid photoresist to a circular shape, but also prevents the sliding of the liquid photoresist, and the non-slip height ratio KC may be increased to 0.4. With the depth of the concave base, KC is getting bigger and bigger. For recesses with a depth of 10 microns, a non-slip height ratio of up to 0.5 can be achieved. Compared with the base, the concave base is relatively reliable, effectively avoid the lens sliding. A microlens array having an inclination angle of 25° can be obtained by using the proposed manufacturing method. The proposed method facilitates mass production to achieve a high yield asymmetric microlens suitable for use in a light control film which can improve the brightness and contrast of a reflective liquid crystal display.

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穩健可靠的傾斜微透鏡陣列創新製程

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摘　要

本研究創新開發一個穩健而可靠的非對稱微透鏡陣列創新製程，利用舉離法在晶圓上形成一凸起或凹陷的銅金屬基座，再進行光阻塗佈之後，透過光罩對位方式來進行曝光，顯影之後便可獲得圓形光阻柱形成於基座上，利用銅金屬基座改變光阻在完全熱熔之後液態光阻與基座之間的接觸面積與接觸型態，進而改變液態光阻的表面張力，當晶圓倒置斜放之後，光阻熱熔時銅金屬基座除了可以精確控制液態光阻的底面形狀之外，也可有效防止液態光阻滑移，可以製作出高度較高、曲率半徑較小的非對稱微透鏡陣列。本研究開發光控膜所需之非對稱微透鏡陣列能聚集多種角度之環境入射光，使折射光有效的分佈於觀賞視角內以大幅提升顯示器反射影像之亮度、對比度、視角及均勻性，並將大部分的炫光排除在視角之外，以期未來可以增進光源之效率與解析度。

關鍵詞：非對稱微透鏡、光控膜、舉離法