Fabrication of gapless triangular micro-lens array

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Abstract

This study presents a new process to fabricate gapless triangular micro-lens array (GTMA) optical film. The process includes ultraviolet (UV) lithography, photoresist reflow process, Ni–Co electroplating and hot embossing technique. After photoresist triangular column array is defined by UV lithography, reflow technique is applied to melt photoresist triangular column array into the shape of triangular micro-lens array. With this reflowed triangular micro-lens array, metal Ni–Co is deposited and covered uniformly on the triangular micro-lens array using electroplating process. The growth rate of Ni–Co is controlled at 0.4–0.6 μm/min at electroplating current density of 1 A/dm² (ampere square decimetre, ASD). After this electroplating process, a mold of GTMA is obtained, which is served as the primary mold. Next, with passivation technique applied on this primary mold’s surface, a secondary mold is obtained by applying the electroplating process again. This secondary mold is served as master for the subsequent hot embossing process to replicate the GTMA pattern onto polymeric material of polymethyl methacrylate (PMMA) sheet. The Ni–Co mold with hardness over hardness of vicker (Hv) 650 is obtained. The stiffness and hardness of the mold play important roles in GTMA hot embossing process. In addition, this PMMA-based GTMA film used as optical film offers a 100% fill factor and high optical coupling efficiency to improve luminance. The optical measurement shows that this optical film with GTMA pattern increases 15.1% of luminance for backlight module (BLM) of liquid crystal display (LCD).

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1. Introduction

Integrated micro-lens array is attracting more attention for various applications in the field of optical communication, optical storage, and digital displays. It plays a very important role in micro-optical components such as video cameras, video phones, compact-disc data storages, robotic visions, optical scanners, and high-definition projection displays. The major objective of micro-lens is to increase the coupling efficiency of optical system, for example, enhance the brightness of backlight module (BLM) for liquid crystal display (LCD) and increase the efficiency of optical switches. Ezell [1] applied micro-lens technology to enhance optical intensity output in a laptop display.

Some fabrication methods of refractive micro-lens using photoresist reflow technique were reported by Refs. [2–5]. Yang et al. [6] used a modified reflow process to fabricate micro-lens with high fill factor. In their study, the gapless square micro-lens arrays were obtained on the silicon substrate. Gapless hexagonal micro-lens arrays were fabricated by thermal reflow process and a mathematical model was developed to predict the profile of micro-lens [7]. Micro-optical components fabricated by deep X-ray lithography show great potential for mass production [8]. Micro-optical components with lateral dimensions in the micro-meter range and height up to several hundreds of micrometers were achieved. Then, a process of molding (either hot embossing or injection molding) was required to fabricate the micro-optical components in mass production [9,10]. However, the cost of synchrotron radiation facility is considerably more expensive than ultraviolet (UV) exposure system. On the other hand, micro-optics printing technology offers a low cost process to form circular micro-lens arrays [11].

Multi-photolithography process was used to fabricate diffractive micro-lens array to increase diffractive efficiency, but it needed rigorous and expensive alignments [12]. The diffractive optical devices were fabricated by a novel partial etching method, based on the scalar diffraction theory and computer...
This study presents a new process to fabricate GTMA optical film. This process mainly includes conventional UV lithography, photoresist reflow technique, Ni–Co electroplating, and hot embossing process. The fabrication process of GTMA mold is schematically illustrated in Fig. 2. First, AZ 4620 photoresist triangular column array is defined by lithography process (see Fig. 2(a)), and then it is heated up over its glass temperature of 150 °C ($T_g$) of the photoresist. The photoresist changes from the shape of triangular column to the triangular micro-lens profile ideally by surface tension, and the triangular micro-lens structure is obtained (see Fig. 2(b)). Next, Ni–Co deposits and covers uniformly on the reflowed photoresist triangular micro-lens structure using electroplating technique. Value of ampere square decimeter (ASD) is controlled at 1 A/dm$^2$ to obtain a dense and smooth GTMA mold structure. A mold of GTMA is formed gradually, as shown in Fig. 2(c). After a period of time, a mold of GTMA is completed (Fig. 2(d)). The geometric design and the layout of photoresist column (Fig. 2(a)) influence the fill factor of GTMA mold significantly. The fill factor of this GTMA mold is 100%. In this study, different micro-lens arrays with 100% fill factors were studied. Fig. 3 illustrates a schematic comparison between these micro-lens arrays. Each lens has the same dimension of circumscribed circle (excircle) of 50 μm in radius. It reveals that compared to the other two kinds of micro-lens arrays, as shown in Fig. 3(b) and (c), respectively, the layout of GTMA (see Fig. 3(a)) has the largest number of lenses (about 28 lenses) in the same confined area of 300 μm × 300 μm. The gapless square and hexagonal micro-lens arrays only show about 16 and 14 lenses, respectively.

Trace Pro software is applied to simulate the above-mentioned micro-lens arrays. The parameters for the simulation are set as: polymethyl methacrylate (PMMA)-based micro-lens array with 25 mm × 5 mm in area, 1 mm in thickness, and each single lens with the same excircle of 50 μm in radius. The simulated result shows that when a input Gauss-mode laser with peak power of 60 kW/m$^2$, as shown in Fig. 4(a), goes through these three different kinds of micro-lens arrays, the optical coupling power output of gapless square micro-lens array, gapless hexagonal micro-lens array, and GTMA, are 27.5, 20 and 40 kW/m$^2$. It reveals that GTMA has the highest optical coupling power output. The simulated result of the coupling power distribution is shown in Fig. 4(b)–(d), respectively. The optical coupling efficiency of GTMA is better than those of square and hexagonal micro-lens arrays. Thus, GTMA exhibits good optical characteristic for various applications such as flat displays, optical sensors, optical recorders and projectors.

In addition, Ni–Co mold with hardness of Hv 650 is developed. With such stiffness and hardness, it promises that the pattern on GTMA mold is successfully transferred onto PMMA after hot embossing process.

2. Process procedures

2.1. Reflow process

Four-inch silicon wafer as substrate including RCA process and dehydration baking, etc. was prepared. Then, the wafer was sent to prime the HDMS and spin coating photoresist AZ 4620 (Fig. 5(a)). The spin condition was set at 600 rpm for 30 s. Twenty-two micrometers thick of the photoresist was obtained. Then, the wafer was sent to the mask aligner to expose about 90 s followed by soft-baking at 100 °C. The dosage of the exposure was 360 mJ. After developing, the triangular column array on the silicon substrate is obtained (Fig. 5(b)).

Finally, this structure was heated to the temperature over the glass temperature of photoresist. The photoresist triangular columns were melted and the photoresist profile was changed into a triangular half-spherical shape by the surface tension.
Fig. 2. Sequential simulated evolution of the mold of GTMA: (a) pattern of triangular column array using lithography process; (b) formation of triangular micro-lens using reflow process; (c) growth of microstructure using Ni–Co electroplating process; (d) primary master mold of GTMA.

effect. Fig. 5(c) shows that the original triangular column array was changed into the triangular micro-lens array.

2.2. Ni–Co electroplating

After the triangular micro-lens array is completed, Ni–Co electroplating technique is applied to transfer the resist pattern into metal Ni–Co mold. The metallization process includes the following five steps: first, Ni thin film is sputtered on the triangular reflowed structure surface, which is served as seed layer (Fig. 6(a)).

Second, Ni–Co electroplating technique is used to form the Ni–Co mold. The deposition rate of Ni–Co is controlled at 0.4–0.6 µm/min at electroplating current density of 1 A/dm².
Fig. 3. Schematic illustration of number of lenses in a same area of 300 μm × 300 μm: (a) gapless triangular micro-lens arrays with 28 lenses; (b) gapless square micro-lens arrays with 16 lenses; (c) gapless hexagonal micro-lens arrays with 14 lenses.

Metal Ni–Co deposits uniformly on the designed reflowed triangular micro-lens array template. After a period of time, Ni–Co mold is completed, which is known as primary master mold (Fig. 6(b)).

Third, passivation treatment is applied on the surface of the primary master mold (Fig. 6(c)). This treatment is to sputter silver (Ag) thin film of 250 nm in thickness on the surface of the primary master mold. A direct current (dc) sputtering gun is used to deposit the Ag thin film. The sputtering parameters include sputtering power of 150 W and bias voltage of 1000 V.

Fourth, Ni–Co electroplating process is applied again to deposit Ni–Co on the Ag thin film to obtain the inverse mold of the primary master mold. Since the adhesion between Ag thin film and Ni–Co is poor, the two molds are separated easily after the electroplating is completed. According to the above processes, the inverse mold of primary master mold, which is known as secondary master mold (Fig. 6(d)), is fabricated. The ingredient and condition of Ni–Co electroplating bath are listed in Table 1. The hardness of the Ni–Co mold over Hv 650 is obtained. Its residual stress after electroplating process is below 1.5 kg/mm².

Fifth, chemical mechanical polishing (CMP) is applied to flatten the mold (Fig. 6(e) and (f)). Finally, the secondary master mold is served as master mold for hot embossing process to duplicate the pattern of GTMA mold onto polymeric material PMMA sheet (see Fig. 6(g)). After demolding, PMMA-based GTMA is obtained (Fig. 6(h)).

2.3. Molding process

In the study, experimental parameters include hot embossing time, applied loading force, and hot embossing temperature. The PMMA sheet with 1 mm in thickness is purchased from Hsintou Company in Taiwan. Its glass transition temperature and average molecular weight are 105 °C and 600,000 g/mol, respectively.

In the experiment, PMMA is used as micro-lens material in hot embossing process. The reason to select PMMA is that the material is very suitable for optical devices because of the physical properties and the optical properties as shown in Table 2. PMMA has a higher transmittance than those of polycarbonate (PC) and polystyrene (PS), respectively. Besides, its low $T_g$ (105 °C) is good for hot embossing process to reduce embossing pressure and cycle time. Its low absorbent ratio (0.2%) and stiff mechanical property (high hardness) enhances its ability for IR coating. PMMA in various thicknesses under different temperature conditions is conducted to study the shrinkage effect. Thermal mechanical analyzer (TMA) from SETARAM Company is used to test the shrinkage. The result shows that the shrinkage of PMMA is a function of hot embossing temperature. The percentage of shrinkage will become less obvious with decrease in thickness of PMMA sheet, as shown in Fig. 7(a). The relative difference is too small. Temperature plays an important role on the shrinkage effect.

Due to the micro-meter-scale structure, molding is also one of the key factors to the GTMA fabrication. The experimental set-up of hot embossing is schematically illustrated in Fig. 7(b).

3. Results and discussions

Compared with gapless square micro-lens array and hexagonal micro-lens array, GTMA has the largest number of micro-
Table 1
Ni–Co alloy electrolyte composition

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni concentration</td>
<td>70 g/L</td>
</tr>
<tr>
<td>Co concentration</td>
<td>1–20% (w/o) in sol.</td>
</tr>
<tr>
<td>Boric acid</td>
<td>30–40 g/L</td>
</tr>
<tr>
<td>Current density</td>
<td>1–10 Adm$^{-2}$ (ASD)</td>
</tr>
<tr>
<td>pH</td>
<td>4.0 ± 0.5</td>
</tr>
<tr>
<td>Temperature</td>
<td>55 ± 1 °C</td>
</tr>
<tr>
<td>Agitation</td>
<td>Magnetic stirrer</td>
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</table>

Table 2
Comparison of various optical materials

<table>
<thead>
<tr>
<th>Property</th>
<th>Glass</th>
<th>PMMA</th>
<th>PC</th>
<th>PS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific weight (g/cm$^3$)</td>
<td>2.4–5.2</td>
<td>1.19</td>
<td>1.20</td>
<td>1.4</td>
</tr>
<tr>
<td>Absorbent ratio (%)</td>
<td>–</td>
<td>0.2</td>
<td>0.1–0.3</td>
<td>&lt;0.4</td>
</tr>
<tr>
<td>Transmittance (%)</td>
<td>90–91</td>
<td>92–95</td>
<td>87–89</td>
<td>88–92</td>
</tr>
<tr>
<td>Refractive ratio</td>
<td>1.42–1.92</td>
<td>1.49</td>
<td>1.59</td>
<td>–</td>
</tr>
<tr>
<td>Glass transition temperature, $T_g$ (°C)</td>
<td>500–720</td>
<td>105</td>
<td>149</td>
<td>130</td>
</tr>
<tr>
<td>Hardness</td>
<td>–</td>
<td>M92–100</td>
<td>M70</td>
<td>M60–90</td>
</tr>
</tbody>
</table>

lens in the same area. It means that GTMA has the highest coupling efficiency. Coupling efficiency is defined as follows:

\[
\text{Coupling efficiency} = \frac{\text{output power}}{\text{input backlight power}}
\]

Therefore, in this study, a new method to fabricate GTMA is realized. When the reflowed triangular micro-lens array distributes as shown in Fig. 8(a), the profile of GTMA mold is obtained eventually. Fig. 8(b) shows that the reflowed triangular micro-lens array is covered with Ni thin film on its surface using sputtering. This Ni film is served as seed layer for electroplating. Then, Ni–Co is deposited on the designed reflowed triangular micro-lens by electroplating as shown in Fig. 8(c) and (d). The electroplating deposition rate of Ni–Co is about 0.4–0.6 μm/min at 1 A/dm$^2$. Ni–Co deposition is controlled uniformly onto the reflowed triangular micro-lens array template. After several hours of electroplating,
the volume of Ni–Co covering on the reflowed triangular micro-lens array is increased and gets thicker. Next, the edge of each triangular shape extends gradually and touches with each other as shown in Fig. 8 (e). Once the edge contacts with each other, a clear interface is created in which the growth of Ni–Co is constrained. Finally, the Ni–Co micro-structure forms a GTMA mold (see Fig. 8(f)) which is used as primary master mold.

To obtain the secondary master mold, the primary master mold was treated a passivation treatment on its surface. Then, it was hung at cathode during electroplating. For a period of time, the inverse mold of the primary master, which is known as secondary master mold, is fabricated. It is worth noticing that the primary and the secondary master mold are easily separated due to the prior passivation treatment at the primary master mold surface.

With the secondary master mold, hot embossing process to fabricate PMMA-based GTMA was realized. The experimental
parameters include hot embossing time, applied loading force, and hot embossing temperature. In this study, 1 mm thick PMMA is used for hot embossing process. When the applied loading force on the secondary master mold and PMMA sheet reaches 100 N (see Fig. 7), the secondary master mold and PMMA sheet are both heated up to (a temperature) 175 °C. At this temperature (175 °C), which is higher than the glass transition temperature of PMMA, 105 °C, PMMA shows less variation in shrinkage. Then, the applied loading force is increased to 1000 N within 5 s and held for 120 s. Next, without any anti-stiction substance applied, PMMA is demolded from the secondary master mold after the temperature is dropped below the PMMA’s glass transition temperature. As a result, the pattern on the secondary mold is successfully transferred onto the PMMA sheet.

Fig. 6. Schematic flow chart of gapless triangular micro-lens process: (a) sputtering Ni thin film onto the triangular half-spherical structure as seed layer; (b) to get the primary master mold by electroplating Ni–Co mold; (c) after electroplating, passivation treatment on the surface of the primary master mold; (d) the secondary electroplating to fabricate the secondary master mold; (e) to level the surface by CMP process; (f) demold, and get the master mold; (g) by hot embossing process, to fabricate the micro-lens array; (h) demold, and get the gapless triangular micro-lens array.

Fig. 7. Hot embossing process: (a) shrinkage of PMMA as function of temperature; (b) hot embossing set-up.
Fig. 8. Sequential evolution of Ni–Co electroplating process to form the mold of GTMA: (a) the triangular column array change to the half sphere array after reflow process; (b) sputtering Ni thin film onto the triangular half-spherical structure as seed layer; (c) Ni–Co electroplating; (d) growth of the triangular half-spherical structure; (e) interface created; (f) final shape of GTMA mold.

With this method, PMMA-based GTMA is successfully fabricated. To yield the desired results, the accuracy of final product dimension should be controlled within 1–2 μm. There are a lot of parameters affecting the reproducibility of the process such as electroplating ASD, hot embossing force and hot embossing temperature. The PMMA-based GTMA is used as optical film for LCD application. The optical thin film is applied to enhance the luminance of the light source due to its gapless 100% fill factor and high coupling efficiency. Fig. 9 reveals that when Gauss-mode laser light passes through GTMA, it scatters the light distribution on a screen. It is worth noticing that focal spot is observed clearly. It means that the hot embossed GTMA can
function as refractive lens purpose. Besides, GTMA is combined with BLM in order to replace the traditional BEF. The measurement set-up is shown in Fig. 10. The luminance of backlight only with diffuser is 737.6 cd/m² and the luminance of backlight with both diffuser and GTMA is 849.1 cd/m². The result shows that the luminance increases 15.1%.

4. Conclusion

This study presents a new process to fabricate GTMA optical film. The process includes conventional UV lithography, photoresist reflow process, Ni–Co electroplating and hot embossing technique. The Ni–Co mold with hardness over than Hv 650 is presented. It plays an important role in GTMA mold fabrication. The Ni–Co is deposited and covered on the reflowed triangular half-spherical micro-lens substrate uniformly by electroplating process. The growth rate of Ni–Co is controlled at current density of 1 A/dm². The mold is served as master for hot embossing process to replicate the array pattern onto PMMA sheet. In addition, this fabrication process of GTMA offers a 100% fill factor to improve overall light efficiently. The luminance of backlight only with diffuser is 737.6 cd/m² and the luminance of backlight with both diffuser and gapless triangular micro-lens array is 849.1 cd/m². The measurement shows GTMA increases 15.1% of the luminance in BLM application.

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References


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