A novel method to fabricate gapless hexagonal micro-lens array

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Abstract

This study presents an innovative process to fabricate gapless hexagonal micro-lens array to replace expensive grey-mask method. The process includes conventional UV lithography, photoresist reflow technique, Ni–Co electroplating with high hardness and hot embossing process. The Ni–Co electroplating process with hardness larger than Hardness of Vicker (Hv) 650 plays an important role in gapless hexagonal micro-lens fabrication. The Ni–Co is deposited and covered on the reflowed half-spherical micro-lens template, uniformly by electroplating. After the electroplating process is finished, the profile of gapless hexagonal micro-lens array can be obtained known as primary master mold. The inverse primary mold was then fabricated, which is known as secondary master mold. Subsequently, the secondary master mold served as master for hot embossing process to replicate the array pattern onto polymer material sheet. In addition, the innovative fabrication process of gapless hexagonal micro-lens array can offer a 100% fill factor to improve overall light efficiently.

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1. Introduction

Integrated micro-lens array provides the interesting applications for various fields such as liquid-crystal displays (LCDs), mobile phone panels, and personal digital accessories (PDAs). The major objective of using micro-lens array is to enhance the brightness of illumination and simplify the light guide module construction. In a laptop display, a 25% increase in light output was reported while using micro-lens technology [1]. The miniaturization of micro-optics promises to revolutionize many electro-optical systems—from video cameras, video phones, compact disk data storage to robotics vision, optical scanner, and high-definition projection displays [2]. Both higher accuracy and lower cost of micro-lens fabrication methods are needed to meet the rapid growth of commercial devices.

Conventional fabrication methods of refractive micro-lens array are photoresist reflow technique [3,4,5,6]. The photore sist cylinders are firstly formed by lithography process and heated to temperature above the glass temperature (Tg) of the photoresist. Surface tension causes the photore sist cylinders to attain spherical shape ideally. Lee et al. used the modified LIGA process to fabricate micro-lens array by melting the deep X-ray-irradiated pattern in the PMMA substrate [7]. Using deep X-ray lithography to fabricate micro-optical components shows great potential for mass production [8]. Micro-optical components of desired shape with smooth and vertical sidewalls, lateral dimensions in the micrometer range, and heights up to several hundred micrometers can be achieved.

Followed by a molding process (either injection molding or hot embossing), the fabrication of optical components in mass production can be achieved [9,10]. But synchrotron
radiation is considerably expensive option than UV exposure of thick photoresist. On the other hand, micro-optics printing technology offers printing the number of droplets on substrate and forming circular micro-lens array [11]. Micro-lenses ranging from 20 μm to 5 mm in diameter have been fabricated.

For diffractive optical elements (DOEs), focused ion beam (FIB) technology can directly fabricate diffractive micro-lens array on the substrate [12]. On the other hand, laser-directed writing was used to fabricate micro-lens array. A laser writing system for the fabrication of continuous-relief micro-optical elements in photoresist was described by Gale et al. [13] and Zimmer et al. [14]. Upon the development of very large scale integration (VLSI), coherent arrays of micro-lenses were made in the surface of silicon [15,16]. Furthermore, fabrication of micro-lens array by gray level mask and E-beam writer were described in [17,18], respectively.

The fill factor for a round micro-lens array is considered in orthogonally and hexagonally arranged arrays. Both of them are lower than a hexagonal micro-lens array with a maximum fill factor of almost 100%. The fill factor is defined as the percentage of lens area to the total area and is also influenced by the pixel geometry and lens layout [19]. However, most of the technical literature related to micro-lens array discussed only round geometrical lenses, including DOEs [20,21] and ROEs [22,23,24].

The hexagonal micro-lens array can obtain the maximum fill factor, which means that there are no gaps between the lenses. The gapless lens array can obtain uniform light distribution to control the diffuse angle when a point or line light source goes through it, which is desired for various applications. For LCD, the gapless lens array might replace the diffuser and brightness enhancement film (BEF), which can reduce the cost and the thickness of the LCD. This study presents a modified process to fabricate gapless micro-lens array. The process includes conventional UV lithography, photoresist reflow technique, Ni–Co electroplating with high hardness and hot embossing process. The technique of Ni–Co electroplating process with hardness larger than Vickers ( Hv ) 650 was developed. In this study, Ni–Co electroplating process plays an important role in gapless hexagonal micro-lens fabrication. The deposition rate of Ni–Co was uniformly controlled to cover reflowed half-spherical micro-lens template. When the distribution of the reflowed half-spherical micro-lens template was designed properly, the profile of gapless hexagonal micro-lens array can be obtained, known as primary master mold. Later, the passivation treatment was applied on the surface of primary master mold. Due to the passivation treatment on the primary master mold surface before hand, the reverse primary master mold can be replicated and easily separated from primary master mold, which is known as secondary master mold. Subsequently, the secondary master mold served as master for hot embossing process to replicate the array pattern onto PMMA sheet. The replication process can promise the desired profile as final products.

2. Process procedures

2.1. Reflow process

First, a 4 in. silicon wafer substrate was prepared including RCA process and dehydration baking etc. Then, the wafer was sent to priming process and spin coating photoresist AZ4620 (Fig. 1(a)).

The spin rate was 1000 rpm for 30 s and the thickness of the photoresist was 22 μm. Silicon substrate was sent to the mask aligner to expose it for about 36 s after soft-baking at 90 °C.

The dosage of the exposure was 360 mJ. After developing, the column array on the silicon substrate could be defined (Fig. 1(b)).

Finally, this structure was heated to a temperature above the photoresist glass temperature. The photoresist columns were melted and the surface tension effect changed the photoresist profile into a half-spherical shape known as reflow process (Fig. 1(c)).

2.2. Ni–Co electroplating

After the half-spherical micro-lens array was finished, metal Ni–Co electroplating technique was applied to transfer the resist pattern into Ni–Co mold. The ingredient and condition of Ni–Co electroplating bath are listed in Table 1. The hardness of the Ni–Co mold over Hv 650 can be obtained and its residual stress after electroplating process was below 1.5 kg/mm². The metallization process includes the following steps; first, Ni thin film was sputtered on the half-spherical structure surface served as seed layer (Fig. 2(a)). Then, Ni–Co...
Fig. 2. Schematic flow chart of gapless hexagonal micro-lens process: (a) sputter Ni thin film onto the micro-lens array as seed layer; (b) fabricate the primary master mold by electroplating Ni–Co mold; (c) make passivation treatment on the surface of the primary master mold; (d) fabricate the secondary master mold; (e) planarize the surface by CMP process; (f) demold to get the secondary master mold; (g) fabricate the micro-lens array by hot embossing process; (h) demold and get the gapless hexagonal micro-lens array.

Table 1

<table>
<thead>
<tr>
<th>Ni–Co alloy electrolyte composition</th>
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<tbody>
<tr>
<td>Ni concentration</td>
</tr>
<tr>
<td>Co concentration</td>
</tr>
<tr>
<td>Boric acid</td>
</tr>
<tr>
<td>Current density</td>
</tr>
<tr>
<td>pH</td>
</tr>
<tr>
<td>Temperature</td>
</tr>
<tr>
<td>Agitation</td>
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</table>

The electroplating technique was used to form the Ni–Co mold. The deposition rate of Ni–Co was uniformly controlled by a cathode-rotated mechanism to cover reflowed half-spherical micro-lens template. The electroplated Ni–Co got deposited on the designed, reflowed, half-spherical micro-lens array, known as primary master mold (Fig. 2(b)). Later, the passivation treatment by thermal method was applied on the surface of Ni–Co (Fig. 2(c)). Then, the Ni–Co was electroplated again on the surface with the passivation treatment (Fig. 2(d)). To obtain a high flatness of the electroplated surface, chemical mechanic polishing (CMP) was applied to
Fig. 3. Thermal recipe for passivation treatment.

Table 2
Comparison of varied 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/cm³)</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>96–91</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</td>
<td>500–720</td>
<td>105</td>
<td>149</td>
<td>130</td>
</tr>
<tr>
<td>temperature, T_g (°C)</td>
<td>–</td>
<td>M02–100</td>
<td>M70</td>
<td>M60–90</td>
</tr>
<tr>
<td>Hardness</td>
<td>–</td>
<td>M92–100</td>
<td>M70</td>
<td>M60–90</td>
</tr>
</tbody>
</table>

Finally, the secondary master mold served as master for hot embossing process to replicate the array pattern onto planarize the surface (Fig. 2(e)). Therefore, the inverse mold of primary master mold can be replicated, which is known as secondary master mold. Due to the passivation treatment on the surface of primary master mold, secondary master mold can be easily separated from primary master mold (Fig. 2(f)).

Finally, the secondary master mold served as master for hot embossing process to replicate the array pattern onto PMMA sheet (Fig. 2(g)). The replication process can transfer the pattern of secondary master mold on PMMA as final products (Fig. 2(h)). The parameters of thermal passivation treatment are listed in Fig. 3.

PMMA sheet (Fig. 2(g)). The replication process can transfer the pattern of secondary master mold on PMMA as final products (Fig. 2(h)). The parameters of thermal passivation treatment are listed in Fig. 3.

Fig. 5. Different shape of micro-lens with different fill factor: (a) gap hexagonal micro-lens with fill factor 90%; (b) half-spherical micro-lens with fill factor 45%; (c) rectangular micro-lens with fill factor 95%; (d) gapless hexagonal lens with fill factor 100%.
2.3. Molding process

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

In this experiment, PMMA is used for hot embossing process. The reason to select PMMA as micro-lens material is that the material is very suitable for optical devices because of physical properties, optical properties and ability for IR coating, etc., as shown in Table 2. Various PMMA in thickness under different temperature condition was investigated to realize its shrinkage effect. The result shows that its 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. 4(a).

Due to the micrometer-scale structure, molding is also one of the key factors to the micro-lens fabrication. The experimental setup of hot embossing is schematically illustrated in Fig. 4(b).

3. Results and discussions

The fill factor for different shape of micro-lens array was investigated in our lab. As shown in Fig. 5, hexagonal micro-lens with gap, half-spherical micro-lens, rectangular micro-lens with gap and gapless hexagonal micro-lens array were fabricated. It can be clearly identified that the gapless hexagonal micro-lens array has the highest percentage of lens area to total area, which means that it has the highest fill factor. Therefore, in this study, a novel method to fabricate gapless hexagonal micro-lens array was presented. Besides, different dimensions of gapless hexagonal lenses were designed and fabricated.

When the reflowed half-spherical micro-lens array distributes as shown in Fig. 6, the profile of gapless hexagonal micro-lens array can be obtained. The evolutional process of the gapless hexagonal micro-lens array is shown step by step in Fig. 7. The first step is to metalize the reflowed half-spherical micro-lens template by sputtering Ni on the surface as seed layer. Then, the Ni–Co was deposited on the designed reflowed half-spherical micro-lens array by electroplating as shown in Fig. 7(a). The deposition rate of Ni–Co by electroplating was uniformly controlled to cover the reflowed half-spherical lens template. After electroplating for some hours, the volume of Ni–Co covering on the reflowed half-spherical lens keeps increasing and getting larger and larger. Later, the edge of each half-spherical shape approaches gradually and touches each other (Fig. 7(b and c)). Once the edge contacts each other, a clear interface will be created in which the growth of Ni–Co will be constrained (Fig. 7(d and e)). Finally, the Ni–Co microstructure with a gapless hexagonal micro-lens profile was formed (Fig. 7(f)) which is used as primary master mold.

To obtain secondary master mold, the primary master mold received a passivation treatment on its surface using chemical solution. Then the primary master mold was put at cathode pole during electroplating. For a period of time, the reverse mold of primary master mold can be fabricated, which is known as secondary master mold. It is worth noticing that the
primary and secondary master mold can be 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 gapless hexagonal micro-lens ar-
ray was tested. In the study, experiment parameters include
hot embossing time, applied loading force, and hot emboss-
ing temperature. In the experiment, 1 mm PMMA is used
for hot embossing process. When the applied loading force
100 N on the secondary master mold and PMMA is arrived
(see Fig. 4), both of the secondary master mold and PMMA
sheet were heated to a temperature 175 °C, where PMMA
shows less variation in shrinkage, and which is higher than
the glass transition temperature of PMMA, 105 °C. Then,
the applied loading force is increased to 1000 N within 5 s
and the force is held for 120 s. Finally, PMMA was de-
molded from the secondary master mold after the tempera-
ture was dropped below the PMMA’s glass transition tem-
perature. As a result, the pattern on the secondary mas-
ter mold can be successfully transferred onto the PMMA
sheet.

If the distribution of the reflowed half-spherical micro-
 lens array is designed differently, it can obtain various pro-
files of hexagonal micro-lens array (Fig. 8). When the pitch
of reflowed half-spherical micro-lens array is designed, var-
ious different dimensions of hexagonal micro-lens array can
be fabricated. Fig. 9 shows different dimensions of PMMA-
based gapless hexagonal micro-lens array of scanning elec-
tron microscope (SEM) image after hot embossing process.
Therefore, with this method, gapless hexagonal micro-lens
array can be successfully fabricated, which can be used as a diffuser to enhance the uniform degree of the light source because it is gapless and its fill factor is 100%. It also reveals that when light passes through different gapless hexagonal micro-lens array, it shows that different light distribution was formed. It is worth noticing that focal spot can be observed clearly, which means the hot-embossed PMMA-based hexagonal micro-lens array can function as refractive lens purpose.

The surface roughness of hot-embossed PMMA-based hexagonal micro-lens array was measured. The result is shown in Fig. 10. The average roughness is less than 50 nm. In
the future study, improving the electroplated surface’s roughness will be explored.

4. Conclusion

Integrated micro-lens array provides interesting applications for various fields. The major purpose is to enhance the brightness of illumination and simplify the light guide module construction. In this study, the gapless hexagonal micro-lens array can obtain uniform light distribution that form point or line source and also can control the diffuse angle. The gapless hexagonal micro-lens array is obtained from Ni–Co electroplating process. This study presents an innovative process to fabricate gapless hexagonal micro-lens array. The process includes conventional UV lithography, photoresist reflow technique, Ni–Co electroplating with high hardness and hot embossing process. The technique of Ni–Co electroplating process with hardness larger than Hardness of Vickers (Hv) 650 was developed. The Ni–Co mold served as master for hot embossing process to replicate the array pattern onto polymer material sheet. The replication process can promise the desired profile as final products.

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References


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