Replication of Microlens Arrays by Gas-Assisted Hot Embossing

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This article reports an effective method for mass-production of 300 × 300 microlens arrays. A microlens array master is formed by imprint lithography and photo-resist reflow at room temperature. The electroforming is then applied to fabricating the Ni mold from the master, followed by the gas-assisted hot embossing to replicate the microlens arrays. The isotropic gas pressure on the plastic film against the Ni mold produces plastic microlens array of high quality and uniformity. The effects of processing parameters including the processing temperature, pressure, and time on the replication quality of microlens arrays were investigated. The experimental results show that the filling of molded microlens significantly increases as the processing temperature and pressure increase. Under the condition of 180°C, 3.9 MPa for gas pressure, and 90 seconds processing time, the arrays of polycarbonate microlens of diameter 150 µm and pitch 200 µm have been successfully replicated. The deviation of replicated microlens from the mold is less than 0.25%. Compared with the conventional hot embossing process, the new replication method offers more uniform embossing pressure distribution. The great potential for replicating microlens array on large plastic films with high productivity and low cost was demonstrated.

Keywords Electroforming; Gas-assisted; Hot embossing; Imprint lithography; LIGA; Microlens array; Reflow; Replication; Uniform pressure; Uniformity.

INTRODUCTION

In recent years, microlens arrays have had a large field of application, for example optical interconnection, optical data storage, display devices, and so on. There have been several fabrication methods for microlens arrays such as a photo-resist reflow [1, 2], excimer laser ablation [3], gray scale photolithography [4], ink-jet fabrication [5], hot embossing of plastic material on a lens array mold made by focused ion beam milling [6], and polymer replication of microlens arrays by injection molding with Ni mold, which is fabricated by modified Lithographie GaVanoformung Abformung (LIGA) process [7].

Among these fabrication methods, hot embossing and injection molding are regarded as the least costly mass-production process to replicate microlens arrays. However, injection molding process is limited by the complicated tool design and expensive machine. The conventional hot embossing is comparatively inexpensive, but there are inherent problems due to the pressing mechanism using hot plates of press. The pressure between the mold and plastic substrate is nonuniform [8]. The mold feature and contact friction have significant effects on the mold filling of hot embossing process [9]. In addition, the focused ion beam and modified LIGA techniques are expensive, time-consuming, and not easily accessible to scientists and engineers in industry.

In this article, a relatively simple and effective procedure for mass-production of microlens arrays is proposed. First of all, a microlens array master is formed by room temperature imprint lithography [10] and photo-resist reflow process. Next, electroforming is carried out to fabricate the metal mold from the microlens array master. Finally, gas-assisted hot embossing is used to replicate microlens arrays.

In this replication technique, a plastic film is placed on the Ni mold with microlens array cavity and the stack is placed in a closed chamber. Upon heating above the glass transition temperature (Tg) of the plastic film, the nitrogen gas is introduced in the chamber to pressurize the stack. Under gas pressure, the polymer material is filled into the microcavities and forms a microlens array structure. Finally, the stack is cooled down, the gas is vented, the chamber is opened and the plastic film is removed from the Ni mold, and a film with microlens array is obtained. The effects of processing temperature, gas pressure, and processing time on the replication quality of microlens arrays are investigated. The surface roughness of fabricated microlens array is also measured and analyzed.

EXPERIMENTAL DETAIL

Fabrication of Microlens Array Mold

Figure 1 shows the procedure for fabricating a microlens array mold. The first step is the room temperature imprint lithography. In this step, a silicon mold insert with 300 × 300 micro-holes array is first fabricated by conventional photolithography and deep reactive ion etching process. Figure 2 shows a SEM image of silicon mold insert and the dimension of micro-holes array cavity. Each hole in the array is of diameter 150 µm, pitch 200 µm, and depth 36.16 µm. Next, a thermoplastic photo-resist layer is coated onto a glass plate substrate which is pressed by the silicon mold insert at room temperature and then baked in vacuum. After the silicon mold insert is peeled off
from the plate substrate, an array of photo-resist cylinders is obtained.

The second step is the photo-resist reflow process. After the cylinders array photo-resist structures are patterned on the plate substrate, the substrate is heated to a temperature higher than the glass-transition temperature of the photo-resist. The surface tension converts the cylinder surface into spherical lens form. The photo-resist microlens array master is obtained. The microlens array master has a diameter of 150 µm, pitch 200 µm, and reflow height 35.56 µm as measured by a surface profiler (Alpha-Step 500, TENCOR, USA).

The final step is Ni-electroforming. In this step, the seed layer of gold of 50 nm thick is deposited on the microlens array master. The gold-coated master with microlens array structure is then placed into an electroforming bath for several hours to form a Ni mold. The mold cavities of microlens array are produced to diameter of 150 µm, pitch 200 µm, and depth 35.88 µm.

**Replication Experiment**

After the Ni mold with microlens array cavity is made, gas-assisted hot embossing is used to fabricate the plastic microlens arrays. Optical grade polycarbonate (PC) films with a thickness of 180 µm and a glass transition temperature of 130°C are used as the raw material.

Figure 3 shows the gas-assisted hot embossing equipment. The machine is composed of a hot-press system, a stainless-steel chamber, nitrogen tank (11.8 MPa max.), a pressure regulator, and valves. The hot-press system consists of a hydraulic cylinder and two heating/cooling plates. The stainless-steel chamber is pressed by the hot-press system to form a closed chamber. The gas pressure can be regulated with the pressure regulator. The mold can be a silicon wafer, glass, nickel mold, or other stamp with microfeatures.

The gas-assisted hot embossing process is similar to the conventional hot embossing process. The whole molding process can be divided into four stages as illustrated in Figure 4.
(1) Heating stage: The plastic film/Ni mold stack was placed in a closed chamber and hot plate was heated to processing temperature (T) above the glass transition temperature (Tg) of the plastic material. During the heating process, low gas pressure is applied to the film to prevent the film from creasing.

(2) Constant temperature and pressing stage: When the processing temperature is reached, the gas was introduced into the chamber to exert gas pressure (P) uniformly over the film, forcing the film into the mold. The softened polymer is filled into the microlens array cavities.

(3) Cooling and packing: After the processing time period (t1 ~ t2), the polymer is cooled down to below the glass transition temperature, while maintaining the pressure (P) to prevent uncontrolled shrinkage and distortion.

(4) De-molding: At the demolding temperature, the gas is vented and the chamber is opened, and the film with microlens array is removed.

To verify the feasibility and uniformity of gas-assisted hot embossing process, the pressure distribution during gas embossing stage is measured by a pressure-sensitive film. The shape and filling of molded microlens is measured by surface profiler (Alpha-Step 500, TENCOR, USA) and inspected by scanning electron microscopy (JSM-5600, JEOL, Japan).

On the other hand, the effects of processing conditions on replication quality of microlens array, including the processing temperature, pressure, and time, were studied. As shown in Table 1, with other parameters fixed at reference states (underlined in Table 1), the effect of each parameter on the replication quality of microlens array during gas assisted hot embossing can be determined.
Figure 3.—Gas-assisted hot-embossing set-up.

![Diagram showing gas-assisted hot-embossing set-up]

Figure 4.—Molding stages.

![Diagram showing molding stages]

Table 1.—Processing conditions in the experiments.

<table>
<thead>
<tr>
<th>Run</th>
<th>Processing temperature (°C)</th>
<th>Processing pressure (MPa)</th>
<th>Processing time (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>140</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>150</td>
<td>20</td>
<td>60</td>
</tr>
<tr>
<td>3</td>
<td><strong>160</strong></td>
<td><strong>30</strong></td>
<td><strong>90</strong></td>
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<tr>
<td>4</td>
<td>170</td>
<td><strong>40</strong></td>
<td>120</td>
</tr>
<tr>
<td>5</td>
<td>180</td>
<td>50</td>
<td>150</td>
</tr>
</tbody>
</table>

Note: Reference parameters are underlined.

RESULTS AND DISCUSSIONS

Pressure Distribution Measurement

The measurement of contact pressures during the embossing stage was accomplished with pressure-sensitive...
film (Fuji Pre-scale Film Co., Ltd., Tokyo, Japan). This product is composed of two parts, a microcapsule layer and a color-developing layer. When pressure is exerted, the microcapsules break and release their substance into contact with the color-developer layer. The color density of the pressure-sensitive film was measured by a densitometer detector FPD-305E. The color density is proportional to the amount of contact pressure.

In this study, the pressure-sensitive film was cut to 6 cm × 6 cm and inserted between the Ni mold and plastic film. The embossing pressure applied to the pressure-sensitive film is about 4.9 MPa.

Figures 5(a) and (b) shows the pressure distribution images of conventional hot embossing and gas-assisted hot embossing, respectively. For conventional hot embossing process, the pressure of the contact area is 3.9 ± 1.2 MPa. The pressure between the mold and plastic film is not uniform. Because of the Ni mold, plastic film and rigid plates of the press machine are not perfectly coplanar, and there exists a variation in molding pressure. For the gas-assisted hot-embossing process, the measured pressure values over the contact area were 4.7 ± 0.1 MPa. The pressure distribution is more uniform over the whole contact area. Because the gas pressure is isotropic, no significant unbalanced forces are applied. The result shows promise for replicating microlens array on large plastic films with high uniformity.

### The Effects of Processing Conditions on Replication Quality of Microlens

The effects of processing conditions on replication quality of microlens, including the processing temperature, pressure, and time, were investigated. The filling height of microlens is measured using surface profiler. Table 2 gives the measured data of the feature height of molded microlens

<table>
<thead>
<tr>
<th>Runs</th>
<th>Processing conditions</th>
<th>Lens 1 Filling height (µm)</th>
<th>Lens 2 Filling height (µm)</th>
<th>Lens 3 Filling height (µm)</th>
<th>Lens 4 Filling height (µm)</th>
<th>Lens 5 Filling height (µm)</th>
<th>Average Filling height (µm)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>T = 140°C, P = 3.9 MPa, t = 90 s</td>
<td>1.21</td>
<td>1.30</td>
<td>1.02</td>
<td>1.15</td>
<td>1.62</td>
<td>1.26</td>
</tr>
<tr>
<td>2</td>
<td>T = 150°C, P = 3.9 MPa, t = 90 s</td>
<td>23.35</td>
<td>23.17</td>
<td>23.43</td>
<td>23.62</td>
<td>23.07</td>
<td>23.33</td>
</tr>
<tr>
<td>3</td>
<td>T = 160°C, P = 3.9 MPa, t = 90 s</td>
<td>30.35</td>
<td>30.28</td>
<td>30.97</td>
<td>30.85</td>
<td>31.07</td>
<td>30.70</td>
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<td>4</td>
<td>T = 170°C, P = 3.9 MPa, t = 90 s</td>
<td>35.12</td>
<td>34.98</td>
<td>35.11</td>
<td>35.26</td>
<td>35.07</td>
<td>35.11</td>
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<td>5</td>
<td>T = 180°C, P = 3.9 MPa, t = 90 s</td>
<td>35.81</td>
<td>35.87</td>
<td>35.79</td>
<td>35.73</td>
<td>35.75</td>
<td>35.79</td>
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<td>6</td>
<td>P = 1.0MPa, T = 160°C, t = 90 s</td>
<td>7.73</td>
<td>7.04</td>
<td>7.57</td>
<td>6.93</td>
<td>7.43</td>
<td>7.34</td>
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<td>7</td>
<td>P = 2.0MPa, T = 160°C, t = 90 s</td>
<td>13.27</td>
<td>13.32</td>
<td>13.62</td>
<td>13.77</td>
<td>13.87</td>
<td>13.57</td>
</tr>
<tr>
<td>8</td>
<td>P = 2.9MPa, T = 160°C, t = 90 s</td>
<td>26.77</td>
<td>26.51</td>
<td>25.95</td>
<td>26.31</td>
<td>26.47</td>
<td>26.40</td>
</tr>
<tr>
<td>9</td>
<td>P = 4.9MPa, T = 160°C, t = 90 s</td>
<td>33.24</td>
<td>33.53</td>
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<td>32.96</td>
<td>33.26</td>
<td>33.24</td>
</tr>
<tr>
<td>10</td>
<td>t = 30 s, P = 3.9MPa, T = 160°C</td>
<td>25.65</td>
<td>26.11</td>
<td>25.85</td>
<td>25.76</td>
<td>26.21</td>
<td>25.92</td>
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<td>11</td>
<td>t = 60 s, P = 3.9MPa, T = 160°C</td>
<td>28.83</td>
<td>29.01</td>
<td>28.55</td>
<td>28.34</td>
<td>28.77</td>
<td>28.70</td>
</tr>
<tr>
<td>12</td>
<td>t = 120 s, P = 3.9MPa, T = 160°C</td>
<td>31.55</td>
<td>30.74</td>
<td>30.95</td>
<td>30.83</td>
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<tr>
<td>13</td>
<td>t = 150 s, P = 3.9MPa, T = 160°C</td>
<td>31.15</td>
<td>31.62</td>
<td>31.35</td>
<td>30.77</td>
<td>31.13</td>
<td>31.20</td>
</tr>
</tbody>
</table>

Figure 6.—Effect of processing temperature on the filling of molded microlens.

Figure 7.—Effect of processing pressure on the filling of molded microlens.
array for the 13 test trials. Five microlenses were randomly selected for each test trial to avoid the possibility of a systematic error.

Figure 6 shows the effect of processing temperature on the filling height of molded microlenses. At the processing pressure of 3.9 MPa and processing time of 90 seconds, when processing temperature increases from 140°C to 180°C, the filling height of molded microlens rises dramatically from 1.26 μm to 35.79 μm. When the processing temperature is low, the viscosity of the polycarbonate material increases. The plastic becomes rigid and limits the material flow into the mold cavity. This could be the reason for the poor replication quality obtained at low processing temperature. On the contrary, a higher temperature is favorable because of the lower viscosity that facilitates polymer flow into the microlens cavity.

Figure 7 shows the experimental results by changing the processing pressure from 1.0 MPa to 4.9 MPa while keeping the processing temperature at 160°C and processing time at 90 seconds. It is found that the filling height of molded microlens increased from 7.34 μm to 33.24 μm.

Figure 9.—SEM and surface profile of produced molded microlens. (a) SEM image of molded plastic microlens array; (b) Surface profile of a single microlens.
Figure 8 shows the measured filling height of molded microlens with respect to the processing time from 30 to 150 seconds under the processing pressure of 3.9 MPa and temperature of 160°C. This measurement reveals that the filling height of molded microlens increases with time from 30 to 90 seconds. Further increase of processing time beyond 90 seconds introduces very small increase in the filling height of molded microlens.

The experimental results show that the processing temperature and pressure are the two most critical processing parameters on replicating of microlens in gas-assisted hot-embossing process. For PC material, under the condition of 180°C, 3.9 MPa gas pressure, and 90 seconds processing time, the arrays of polycarbonate microlens have been successfully replicated. Figure 9 shows a SEM image of molded microlens array and surface profile of a single microlens. A microlens is produced with diameter 150 μm, pitch 200 μm, and filling height 35.79 μm. The deviation of replicated microlens array from the Ni mold is less than 0.25%.

In order to characterize the uniformity of the molded microlens array, the surface profiles of 50 microlenses (randomly selected in a 300×300 array of a microlens) from a single process run are measured. The average diameter is 150.3 μm with a standard deviation of 0.41 μm. The average height is 35.7 μm with a standard deviation of 1.66 μm. These results indicate good uniformity and controllability of the gas-assisted hot-embossing molded microlenses.

The Surface Roughness of Replicated Microlens

To characterize the surface morphology of the molded microlens array, the surface roughness has been measured by atomic force microscope (AFM). Figure 10 shows the AFM image and roughness analysis of a randomly picked microlens from a single lens array. The average surface roughness (Ra) on the microlens top surface is 1.5–3.5 nm, which shows good optical smoothness of the microlens.

Conclusions

In this article, the authors have proposed an effective fabrication method for mass-production of microlens array. A microlens array master is formed by imprint lithography and photo-resist reflow process. The electroforming is then applied to fabricate the Nickel mold from the master. Gas-assisted hot embossing is used to transfer microlens array structure from mold to plastic film. By using the isotropic gas pressure, the high quality and uniform, plastic microlens array can be achieved.

The experimental results show that the filling of molded microlens significantly increases as the processing temperature and pressure increase. The 300×300 microlens array are precisely replicated and show the great potential of using the gas-assisted hot-embossing process for replicating microlens array on large plastic films with high productivity and low cost. This effective can be also used to manufacture micro-optical components such as gratings and waveguides etc.

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References