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AN INVESTIGATION ON THE PROFILE OF MICROLENS BY THE THERMAL REFLOW PROCESS DUE TO SURFACE TENSION AND GRAVITY

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ABSTRACT

Microlens and its mold fabricated by thermal reflow using photoresist have been widely used for forming patterns in different scales. When the photoresist solidifies from melting condition, for example by the reflow process, its profile is formed based on the balance between surface tension and gravity. This research is aimed to investigate the influence of surface tension and gravity on the profile of microlens in thermal reflow process. Theoretical analysis based on the interaction between surface tension and gravity of liquid droplet is first investigated. The result showed that the height to diameter ratio (h/D), or the sag ratio, of the liquid droplet is affected by the Bond number (Bo), a number defined as the ratio of gravity to surface tension. The sag ratio is not sensitive to Bo when Bo is small but the ratio decreases as Bo increases if Bo is over the critical number. Based on the analysis, the critical number for the AZ4620 photoresist on a silicon substrate is 1, corresponding to the critical radius of droplet R=2,500μm. When the size of the droplet is less then the critical size, the profile is mainly controlled by the surface tension and thus the sag ratio is about the same regardless the size. The profile, in contrast, is highly affected by the gravity if the size of the droplet is larger then the critical size. The sag ratio decreases exponentially with respect to Bo in this case. Experiments are also designed and conducted to verify the analysis. Experimental result showed that the sag ratio of the photoresist reduces to 0.065 from 0.095 when Bo increases from 0.0048 to 0.192. The results showed that the trend is consistent to the theoretical model.

1 INTRODUCTION

As products is becoming more smart and smaller in the past decades, together with the fast progress of industrial technologies, photoelectric components in micro scale have been widely used in various consumer products. Dimensions of these micro-scale components, such as microlens, micro grating, micro mirror, micro beam splitter, and micro prism, are from sub-micrometer to several hundred micrometers [1-3]. Among these components, microlens has been widely employed in various industries, including flat panel display, biomedical photonics, optical communication, optical storage, and micro electro-optical-mechanical systems, thus it plays an important role in consumer product industry [1-4]. Various technologies and processes for fabricating microlens have been developed to meet the need in market. Among these technologies, the thermal reflow process has been well adapted to fabricate the microlens or the mold insert because of its simplicity, low fabrication cost and acceptable quality in uniformity and surface roughness.

The profile of a microlens is one of the major factors that affect its optical performance. For example, the focal length and numerical aperture (NA) as well as aberrations of a spherical microlens depend on its surface curvature and height, in addition to the material property [5, 6]. For microlens or its mold insert fabricated by the thermal reflow process, many factors can result in variation of its profile. The external force is the major factor that causes the profile change in the reflow process as the material is in semi-liquid condition during the forming process and can be easily deformed by an external force. Previous work has noticed the effect of substrate due to the interfacial tension between the lens material and the substrate. Therefore substrate with high interfacial tension, for example, has been selected for fabricating high-NA microlens based on this principle [7].

However, the influence of another external force, the gravity, is often neglected in most researches because its effect is not crucial for lens at small size. Schilling *et al*. noticed the combined effect of both external forces and investigated the influence of surface tension and gravity of microlens fabricated by the thermal reflow process. They compared the profile of different microlenses that were placed with face up and face down separately in the reflow process. It is found that

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this effect due to gravity can become critical when the size of the lens increases [8]. Nevertheless it is an issue to investigate the lens profile fabricated by the thermal reflow process under the interaction of the interfacial tension and the gravity. This research is therefore aimed to investigate the profile of microlens, fabricated by the thermal reflow process, under the combined effects of the interfacial tension and the gravity.

2. ANALYSIS OF LENS PROFILE

To investigate the profile of microlens fabricated by the thermal reflow process, we first look at the profile of a droplet on the substrate. Shapiro *et al.* derived the relationship of geometric parameters of a liquid droplet. They can be presented as in equation (1) where R, θ and ρ are the radius of the liquid droplet, the contact angle between the liquid and the substrate and the density of the liquid [6]. The symbols γ_{SG}, γ_{SL}, and γ_{LG} in the equation are the interfacial tensions between the substrate and the atmosphere, between the substrate and the liquid, and between the liquid and the atmosphere.

$$\cos\theta - \left(\frac{\gamma_{SG}-\gamma_{SL}}{\gamma_{LG}}\right) + \left(\frac{R^2\rho g}{\gamma_{LG}}\right)\left[\frac{\cos\theta}{3} - \frac{\cos 2\theta}{12} - \frac{1}{4}\right] = 0 \text{ ---------(1)}$$

Furthermore, the interfacial tension γ_{AB} between two non-mixable phases, A and B, can be represented in equation (2), where Φ is a function of the volume of each phase. It has been found that the value of Φ derived from experiments is between 0.5 and 1.15 [9].

$$\gamma_{AB} = \gamma_A + \gamma_B - 2\Phi(\gamma_A\gamma_B)^{1/2} \text{ -----------------------------(2)}$$

The geometric relationship of a liquid droplet, as shown in figure 1, can be derived as shown in equations (3) and (4) where κ is the height/diameter (h/D) ratio of the liquid droplet.

$$\cos\theta = \frac{1-4\kappa^2}{1+4\kappa^2} \text{ ---(3)}$$

$$\cos 2\theta = \frac{1-24\kappa^2+16\kappa^4}{(1+4\kappa^2)^2} \text{ --------------------------------------(4)}$$

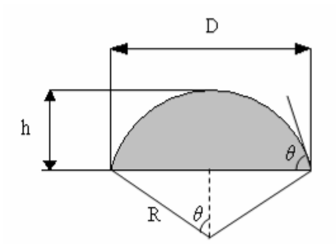

FIGURE 1: Sketch of the geometry of a liquid droplet during the thermal reflow forming process.

Combine equations (2), (3) and (4) with equation (1), we have equation (5) where the ratio $\frac{R^2\rho g}{\gamma_{LG}}$ is called the Bond number Bo [6]. Bo represents the ratio of the droplet weight to the interfacial tension for a liquid droplet with curvature R.

$$\frac{1-16\kappa^4\left(1+\frac{2R^2\rho g}{3\gamma_{LG}}\right)}{(1+4\kappa^2)^2} = \frac{-\gamma_{LG}+1.9(\gamma_{SG}\gamma_{LG})^{1/2}}{\gamma_{LG}} \text{ -------------- (5)}$$

Equation (5) showed that the h/D ratio of a liquid droplet depends upon the Bond number and the interfacial tensions among the liquid, the substrate and the atmosphere. Under the situation of a specific substrate, *e.g.* for a given γ_{SG}, the profile of a liquid droplet then depends upon the material and the weight of the droplet.

Taking water and the photoresist AZ4620 as examples, figure 2 shows the profile (h/D) of droplets of these materials on silicon wafer at different droplet radius R, where γ_{LG} are 0.073 N/m and 0.066N/m for water and AZ4620; γ_{SG} is 0.064N/m for silicon wafer [10]. It shows that the h/D ratio decreases when the Bond number of liquid droplet increases.

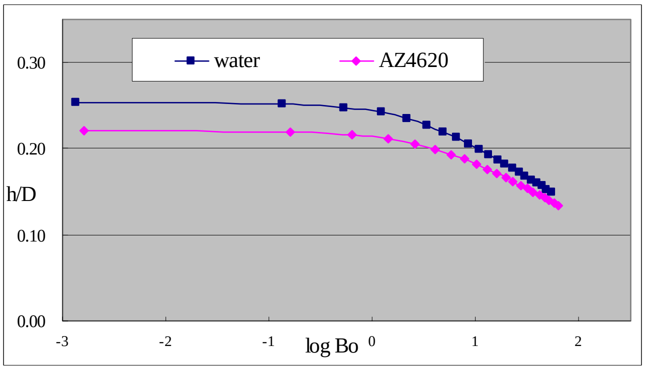

FIGURE 2: Theoretical h/D ratio with respect to the bond number Bo for water and AZ4620.

The figure also shows the profile changes rapidly at certain bond number, called the critical bond number Bo_{cr} which is dependant upon the liquid. For the photoresist AZ4620, the critical bond number is about 1, corresponding to the critical radius around 2,500μm. That is, when the radius of liquid droplet is under 2,500μm, *i.e.* Bo<1, the profile is mainly affected by the interfacial tension. On the other hand, for liquid droplet with radius larger than 2,500μm, gravity plays more important role on its profile.

3. EXPERIMENT DESIGN

Experiments to fabricate microlens using photoresist by the thermal reflow process, as shown in figure 3, were designed to study the feasibility of the theoretical analysis. The photoresist, coated on the substrate, was explored by photo lithography process using a mask of circular apertures. The photoresist was formed into cylinders in micro scale after development. These micro cylinders were then sent to the oven for the thermal reflow process. Each cylindrical photoresist was heated and melted in the process. It is then formed into spherical shape in accordance with the balance between the surface tension and its gravity when the oven was cooled down. In order to observe the effects of gravity, the diameter of the circular array mask is design as 100μm, 200μm, 300μm, 400μm and 500μm. The distance between circles is set to 100μm to avoid interference due to diffraction effect.

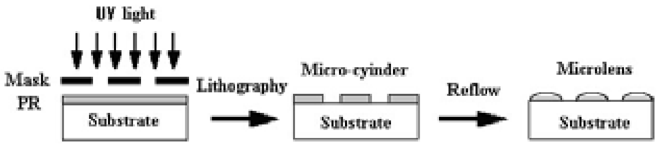

FIGURE 3: Sketch of the thermal reflow experiment

4. EXPERIMENTAL RESULTS

Figure 4 shows the profile of microlens arrays with different diameters from 100µm to 500µm. Images are taken by scanning electronic microscope (SEM) and surface profiler respectively. Photos and images in the figure show that the h/D ratio decreases with the size of microlens. The h/D ratio for microlens with diameter ϕ500µm is the lowest.

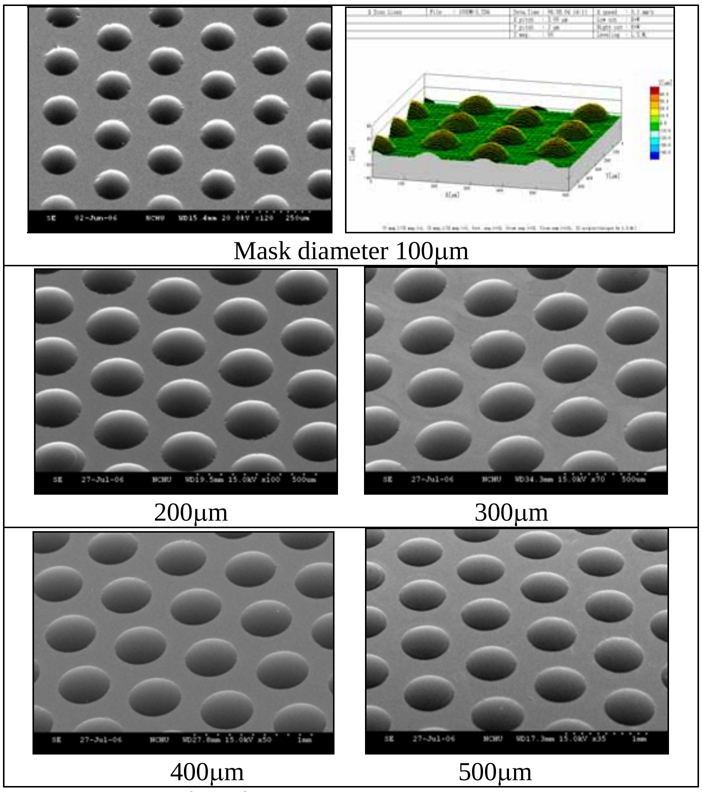

FIGURE 4: Profile of the microlens arrays, measured by SEM and 3D profiler, under different mask diameters.

The heights and diameters of the fabricated microlens arrays are then measured by the optical microscope and the profiler. Data are plotted in figure 5 where the bond number and the h/D ratio are plotted with respect to the diameter. It shows the bond number increases from 0.005 to 0.192 when the diameter increases from 100µm to 500µm. The h/D ratio of the profile decreases from 0.095 to 0.065 at the same time.

The theoretical and experimental results of h/D with respect to the radius of the photoresist are plotted as in figure 6. The theoretical curves are calculated based on equation (5). Two curves are plotted in the figure where the parameter Φ of equation (2) was set to 0.85 and 0.6 respectively. The results showed that experimental data is close to the model with Φ=0.6.

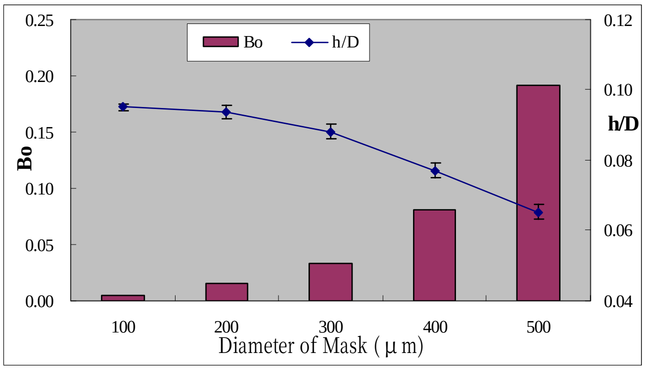

FIGURE 5: The h/D ratios and corresponding Bond numbers of the AZ4620 photoresist for different mask diameters.

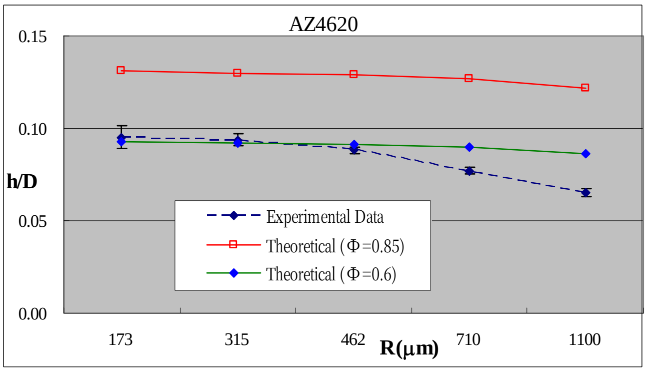

FIGURE 6: Theoretical and experimental results of the AZ4620 Photoresist

5. CONCLUSIONS

This research investigated the effects of surface tension and gravity on the profile of microlens fabricated by photoresist using the thermal reflow process. Investigations are conducted through theoretical analysis and experiments. The results are summarized as follows.

1. The height to diameter (h/D) ratio is affected by the Bond number Bo, an index as the ratio of gravity to surface tension. The ratio decreases when Bo increases. The critical value of Bo is around 1.
2. Simulation using AZ4620 photoresist showed that the critical value of radius is close to 2,500µm for thermal reflow forming. When the radius R is below 2,500µm (Bo<1), surface tension dominates the profile of the photoresist during the thermal reflow forming process. Gravity, on the other hand, is the major factor that affects the profile of the photoresist when its radius is over 2,500µm (Bo>1). It is therefore an important issue to take both surface tension and gravity into consideration when fabricating lens in minimeter-scale by the thermal reflow process.
3. Experiments using AZ4620 photoresist with different diameters of mask has been designed and conducted. The diameter of mask varies from 100µm to 500µm with 100µm increment, corresponding to Bo from 0.005 to 0.192. The results showed that the h/D ratio decreases from 0.095 to 0.065. The change of profile is consistent with

theoretical analysis.

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