An Evaluation of Photoresist Thickness for Semiellipsoid Microlens Fabrication before Thermal Reflow Using the Prolate Spheroid Approximation

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Abstract—**We present a new semiellipsoid microlens fabrication method using the lift-off and alignment exposure processes. The lift-off method is used to create an elliptical copper base before the thermal reflow process. During the photoresist thermal reflow process, the elliptical base can precisely define the bottom shape of the liquid photoresist. The prolate spheroid approximation method is developed to estimate the thickness of elliptic photoresist column required by the semiellipsoid microlens of a certain height, with the error being controlled within ±3%.**

I. INTRODUCTION

Due to the surface tension, only the microlens in spherical cap shape can be produced by the traditional thermal reflow method [1, 2]. In this work, an elliptical copper base is formed on a wafer by using the lift-off process. Based on geometric analysis, we aim to provide a theoretical approach for designing a semiellipsoid microlens shape. Prolate spheroid approximation method will be developed to estimate the thickness of the elliptical photoresist column for the semiellipsoid microlens of a certain height. After the photoresist coating process, exposure should be conducted through mask alignment. And after development, the elliptical photoresist column on the copper base can be obtained. Due to their high surface tension, liquid photoresist tend to minimize their surface trying to achieve a semiellipsoid shape during the photoresist thermal reflow process. The elliptical base can change the contact area and contact mode between the liquid photoresist and copper base, and thus change the surface tension of the liquid photoresist accordingly. During the photoresist thermal reflow process, the elliptical copper base can precisely define the bottom shape of the liquid photoresist.

II. THE PRINCIPLE OF DESIGN-PROLATE SPHEROID APPROXIMATION

To obtain the desired ellipsoid microlens geometric shape, the volume of elliptical photoresist column must be precisely estimated before beginning the thermal reflow process. Fig. 1. illustrates a ellipsoid microlens model and its coordinate system. The general equation for the ellipsoid is:

$$\frac{x^2}{A^2}+\frac{y^2}{B^2}+\frac{z^2}{C^2}=1 \tag{1}$$

where A is the length of semi-axis in the x-direction, B is the length of semi-axis in the y-direction and C is the length of semi-axis in the z-direction. Consider $K(0, 0, k)$ a point on the height of the ellipsoid such that $0 \le k \le C$. The plane parallel to x-y plane going through the point K will intersect the ellipsoid and the filled cap is the volume we want to calculate. The volume of the resulting ellipsoidal cap is given by

$$V_{\text{ellipsoidal cap}}=\pi AB\left(\frac{2C}{3}-k+\frac{k^3}{3C^2}\right) \tag{2}$$

A prolate spheroid can be formed by rotating an ellipse about its major axis; in other words, an ellipsoid with two equal lengths of semi-axes in x and z directions. A prolate spheroid is a spheroid in which the polar axis (y-direction) is greater than the other axes, like a rugby ball. With $k= C-h$ and $C= A= R$, the volume of the prolate spheroid cap can be derived as below

$$V_{\text{prolate spheroidal cap}}=\pi\frac{B}{R}\left(Rh^2-\frac{h^3}{3}\right) \tag{3}$$

where the equatorial radius R of a prolate spheroid is

$$R=\frac{h^2+a^2}{2h} \tag{4}$$

where h is related to the height of microlens and a is the length of minor semi-axis for the elliptical base as indicated in Fig. 2. The equation of an ellipse for y-z plane is

$$\frac{y^2}{B^2}+\frac{z^2}{C^2}=1 \tag{5}$$

b is the length of major semi-axis for the elliptical base as indicated in Fig. 2. Since the ellipse goes through the point $(0, b, k)$ and $C= R$, so

$$\frac{b^2}{B^2}+\frac{k^2}{R^2}=1 \tag{6}$$

From (6) with $k= R-h$, it yields

$$B=\frac{b}{\sqrt{2\left(\frac{h}{R}\right)-\left(\frac{h}{R}\right)^2}} \tag{7}$$

Before melting, the volume of elliptical photoresist column is

$$V_{\text{elliptical column}} = \pi abH \tag{8}$$

where H is the thickness of elliptical photoresist column. We assume that the photoresist volume does not change during the thermal reflow process based on mass conservation, that is

$$\pi abH = \pi \frac{B}{R}\left(Rh^2 - \frac{h^3}{3}\right) \tag{9}$$

The thickness of elliptical photoresist column can be evaluated using the prolate spheroid approximation as

$$H = \frac{B}{R}\frac{h\left(3a^2 + h^2\right)}{6ab} \tag{10}$$

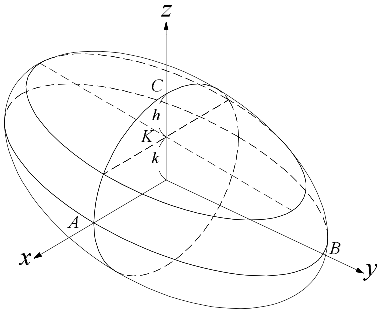

Fig. 1. The coordinate system defined for a semiellipsoid microlens model.

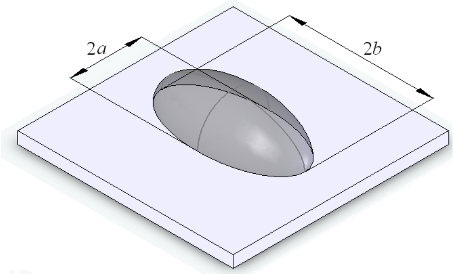

Fig. 2. a and b are the lengths of minor and major semi-axes for a semiellipsoid microlens, respectively.

III. RESULTS AND DISCUSSION

The relationship between theoretical height (h) of the semiellipsoid microlens and experimental results with respect to various the thickness (H) of elliptical photoresist column is depicted in Fig. 3. For example, the lengths of minor and major semi-axes for an elliptical base are 45μm and 90μm, respectively. The semiellipsoid microlens with a height of 20μm can be obtained using the elliptical photoresist column with H=11μm as shown in Fig. 3. According to the experimental result using the elliptical photoresist column with a thickness of 11μm, the height of the semiellipsoid microlens was 20.5μm after thermal reflow process. There were the errors varied within ±3% between the experimental results and the calculated values using (10). This shows that the approximate method is valid. The prolate spheroid approximate solution using (10) is proven feasible and can be a basis for designing ellipsoid microlens in various sizes.

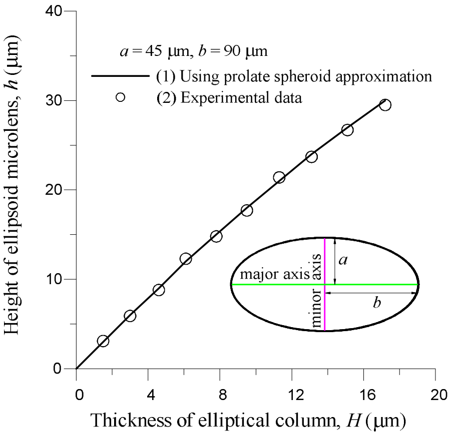

Fig. 3. The height of ellipsoid microlens computed using prolate spheroid approximate method compared with the experimental results.

IV. CONCLUSION

A semiellipsoid microlens can be placed onto the tip of a single-mode fiber end to improve the power coupling efficiency from a laser diode. The semiellipsoid microlens allows increasing the fiber spot size and numerical aperture. We presented a robust and reliable fabrication method for a semiellipsoid microlens array [3, 4, 5].

Before thermal reflow process, prolate spheroid approximation method was developed to estimate the required thickness of the elliptical photoresist column for the semiellipsoid microlens of a certain height. The variations between the actual photoresist thickness and theoretical calculation for making the semiellipsoid microlens were within ±3%. This proved that the theoretical model is feasible.

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