A simple process optimization route to fabricate curved bionic compound eye array

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Abstract. In this paper, a complete and simple process optimization route for the curved bionic compound eye (BCE) array fabrication is presented based on digital micromirror device (DMD) maskless lithography. Firstly, based on the study of edge bulge effect in the thermal reflow process, a proper curved BCE structure is designed. Then, through the optimization of multilayer coating process it can obtain a better uniformity of different photoresist layer and accurate thickness. Next, combined the DMD maskless lithography technology with the Poor Man’s dissolution rate monitor (DRM) approach, well-preformed hierarchical cylindrical structure can be simply fabricated. Lastly, the curved BCE structure can be obtained precisely by choosing the reasonable process control parameters, which depended on the study of two-step thermal reflow processes. This process optimization route makes it very easy to realize the curved BCE array structures with different ommatidium shapes. Experimental results showed the effectiveness of our process optimization method. The presented method is expected to provide a fast, economic and simple strategy for curved BCE array fabrication.

1. Introduction

In recent years, the compound eye structure of insects has attracted extensive attention because of its unique characteristics, which is composed of multiple ommatidia structures distributed on the spherical substrate. And the bionic compound eye (BCE) structure is similar to insect compound eye, which has many advantages, such as light weight, small size, high sensitivity, large field of view, speed measurement and fast tracking, etc. Therefore, it has been widely applied in opto-electronics, bionic medicine and military [1-4], etc. Especially for BCE structure with curved substrate, because it has larger field of view than planar BCE structure, many researchers have studied the structure and its fabrication methods. However, there are still some challenges on how to fabricate high-quality curved BCE structure by some low-cost, simple and effective methods. At present, these methods of fabricating curved BCE mainly include ultra-precision machining technology [5-7], digital grayscale mask lithography [8, 9], graphic copy transfer technology [10] and two-photon femtosecond laser direct writing technology [11-13], etc.

Although these methods have demonstrated their outstanding abilities in fabrication of curved BCE structure, there are still many problems remained to be solved. For the ultra-precision machining technology, it has a strong processing capacity and wide application, but it is limited by expensive
equipment and high machining cost. In order to reduce the fabrication cost of physical mask, the digital grayscale mask lithography is widely used. Although this method can theoretically produce small-size curved BCE structure and has high forming efficiency, it is more complex in the design of digital grayscale mask and difficult to guarantee the forming precision of the final structure. For the graphic copy transfer technology, this method has a simple fabrication process and high molding efficiency, but it is difficult to accurately control the deformation of graphs with small size when pneumatic assisted operation is carried out, which has certain limitations in practical application. In addition, for the current widely used two-photon femtosecond laser direct writing technology, the processing size is not limited and can achieve nano-level accuracy, but its equipment cost is higher and the processing efficiency is lower.

![Figure 1](image1.png)

**Figure 1.** Schematic diagram of the curved BCE array fabrication process. (a) Three layers photoresists via spin coating on a silicon substrate. (b) Hierarchical micro pillars obtained by the DMD-based maskless lithography. (c) The normal contact thermal reflow process. (d) The upside-down thermal reflow process.

![Figure 2](image2.png)

**Figure 2.** Schematic diagram of DMD-based maskless lithography system.

In this paper, we present a simple method for fabricating curved BCE array, which is mainly focused on the study of the complete process optimization route. Based on the edge bulge effect in the thermal reflow [14], a proper curved BCE array structure can be designed. Then, by studying the
multilayer coating process, it can obtain a better uniformity of different photoresist layer and accurate thickness. Next, the DMD maskless lithography technology is used for the exposure process, which has the advantages of high efficiency and low cost. What’s more, taking account of the nonlinearity of thick photoresist development process, the Poor Man’s dissolution rate monitor (DRM) approach [15, 16] was adopted to study the relationship of the exposure and development, which aims to fabricate the well-preformed hierarchical cylindrical microstructure. Finally, by simple two-step thermal reflow processes [17], a curved BCE array with high precision can be obtained conveniently and effectively.

2. Fabrication process and optimization method

The fabrication process schematic for curved BCE array in this study is shown in Figure 1. The fabrication process began with the multi-layers spin-coating processes on a silicon substrate as shown in Figure 1(a), in which the three layers photoresists of sandwich-like structure were obtained. Here, AZ P4620 (a positive photoresist from Clariant) and S1813 (a positive photoresist from Shipley) were used as the top/bottom layer and interlayer, respectively. For the spin coating machine, we adopted the KW-4A coater (Institute of electronics, Chinese academy of sciences) to control the photoresist thickness on the silicon substrate. Then, according to our previous study about the DMD maskless lithography [18-20], the hierarchical pillars were fabricated conveniently, as shown in Figure 1(b). And the schematic diagram of DMD-based maskless lithography system is shown in Figure 2. A mercury lamp (OmniCure™ S1500) is adopted as an exposure light source which is filtered at a wavelength of 365 nm. Then a liquid light guides and an adjustable collimator play the roles of the homogenization and collimation, respectively. In the system, DMD (Texas Instruments) works as the spatial light modulator (SLM), which is consisted of an array of 1024 × 768 micromirrors. It works as virtual masks to generate a series of dynamic masks in real time. Through the DMD, the modulated light projects onto the X-Y motion stage through the objective lens (CFI Plan Flour x4, Nikon Co. Japan). Next, considering the obvious difference of glass softening point (Tg) between two photoresists of AZ P4620 (125 °C) and S1813 (175 °C), two-step thermal reflow processes were adopted. The normal contact thermal reflow was acted as the first thermal reflow, as shown in Figure 1(c). Figure 1(d) showed the second thermal reflow process by the upside-down thermal reflow, which aims to prevent a large deformation of bottom layer structures.

![Figure 3. The diagram of process route for the curved BCE array fabrication.](image-url)

In order to obtain a high precision curved BCE array, it needs to take full account of the impacts of the entire fabrication process. Figure 3 showed the overall diagram of optimization of process route for the curved BCE array fabrication. At the beginning of the design stage, considering the existence of edge bulge effect, the experiment of base thermal reflow molding was carried out for the photoresist used in the experiment. The parameter action rules of normal thermal reflow molding were summarized, and then the curved BCE structure can be designed reasonably and effectively. Then, the multi-layer coating process was optimized to ensure accurate thickness and uniformity of the coating. As for the nonlinearity of thick photoresist development process, the Mack model [21] used for the thin photoresist is no longer applicable. Therefore, the Poor Man’s DRM approach was adopted to study the relationship of the exposure and development, which focused on the interaction laws of the
exposure dose, development depth and development time. Finally, according the proper control of the two-step thermal reflow parameters, such as the reflow temperature and reflow time, the formed curved BCE array can be fabricated precisely.

3. Results and discussion

3.1. The edge bulge effect

Due to thermal reflow process is the key factor in determining the quality of final BCE array, and the edge bulge phenomenon often occurred in thermal reflow process. In order to specifically study the rules of the existence of edge bulge, in our previous study [17] we have systematically studied the relationship between the initial height of the cylinder and the distance of edge bulges in the case of different cylinder diameters, as shown in equation 1.

\[ L_{\text{max}} = \frac{D}{2} = 11.33 \times h \]  

(1)

Where \( L_{\text{max}} \) is the distance of edge bulges, \( D \) is the initial cylinder diameters, \( h \) is the initial height of the cylinder.

In order to ensure that the cylinder shape can be completely reflow into a spherical shape after thermal reflow, the initial cylinder height should meet the following equation 2.

\[ h \geq \frac{D}{22.66} \]  

(2)

Therefore, from the experimental study results we concluded the following laws: (1) For any initial diameter cylindrical shape, in order to assure a good curved BCE shape after thermal reflow, it will have a minimum height in thermal reflow process. And when the pillar height is greater than the minimum height value, the initial cylindrical shape at the height of the dimension can ensure the complete thermal reflow into the desired spherical shape. (2) Through the least square fitting analysis, a straight line with a slope can be obtained. (3) In order to ensure that the cylinder shape can be completely turned into a spherical shape after thermal reflow, the height of the cylinder should be controlled within a certain range.

Therefore, by studying the edge bulge effect, it can effectively avoid the inappropriate design of the initial cylindrical height graphic structure, which aims at improving the molding efficiency and ensuring the quality of the spherical structure after the final thermal reflow.

3.2. The multi-layer coating method

When the photoresist thickness is relatively thick, it is difficult to meet the general requirements by a single coating, which requires multiple coating to reach the required thickness. In the study of coating methods, there are usually direct coating method and multi-layer coating method. When the direct coating method is adopted, the photoresist thickness of each layer cannot be maintained constant due to the influence of the next coating on the previous coating, so this coating method is not adopted in the experiment. For the multi-layer coating method, at the end of each spin coating, it will have a reasonable pre-bake to stabilize the coating layer, which can avoid the influence of the next coating. Then the thickness of different layers can be accurately obtained and the uniformity can be guaranteed.

As can be seen from the example in Table 1, the pre-bake time for the multi-layer coating is shorter than normal single coating. It has the following advantages: on the one hand, it can stabilize the coating layer; On the other hand, it can avoid the effect of the pre-bake of next coating layer on the previous layer.

3.3. The processes of exposure and development

Because the initial pre-formed hierarchical cylindrical structure is fabricated by DMD maskless lithography technology, it is helpful to get high quality preformed cylindrical structure by controlling the exposure dose of the graphics reasonably. The required pre-formed hierarchical cylindrical structure can be obtained by means of one-time continuous exposure. In this experiment, considering
the nonlinearity error of thick photoresist in the development process, the Poor Man's DRM experimental method was introduced to accurately study the spatial distribution relationship between development rate and exposure dose. As Poor Man's DRM method mainly the measurements of multiple contrast curves, such as the research on the relationship among different exposure doses, different development depths and various development times. The experiments about the method have been carried out in our previous study [18]. And from the experimental results, we can obtain the following rules: (1) The dissolution rate of the photoresist increases with the increase of exposure dose under the condition of a certain development time. When the maximum exposure dose exceeds the total exposure depth of the designed contour, the dissolution rate of the photoresist tends to be equal if the exposure dose continues to increase. (2) With a certain exposure dose, the development depth gradually increases with the development time, and tends to be equal when the maximum development depth is reached. (3) With a certain development depth, the higher the exposure dose, the faster the development rate. Therefore, by this method it can effectively reduce the contour error caused by the exposure and development processes.

**Table 1.** The process control parameters by the multi-layer coating method.

| Layer     | Thickness (μm) | Temperature (℃) | Pre-bake time (min) | Normal pre-bake time (min) |
|-----------|----------------|------------------|---------------------|---------------------------|
| Bottom layer | 10             | 100              | 2                   | 6                         |
| Interlayer | 1.5            | 100              | 1                   | 3                         |
| Top layer  | 5.5            | 100              | 3                   | 3                         |

**Figure 4.** The failure diagram of curved BCE structure under different thermal reflow times.

**Figure 5.** The curved BCE structure measured by the Bruker Stylus Profiler.

**Figure 6.** The curved BCE structure with a hexagonal ommatidium shape. (a) and (b) were the designed digital mask graphics, respectively. (c) The image measured by optical microscope.
3.4. The two-step thermal reflow processes

After exposure and development, the curved BCE structure can be obtained by two-step thermal reflow processes. In the previous study [19], we have analyzed about the upside-down thermal reflow strategy, in which theoretical and experimental research are discussed, respectively. And the presented results showed that the strategy is feasible. What’s more, the reasonable control of thermal reflow process parameters is the key to the successful realization of the curved BCE structure. As shown in Figure 4, it shows the forming result diagram under the unreasonable thermal reflow parameters. It can be found that the small microlens array patterns are mixed together in a very short time, and the shapes become fuzzy, so the parameters of thermal reflow need to be strictly controlled.

In order to obtain a high precision curved BCE structure, we tried many experiments about the thermal reflow parameters. In the example, for the parameters of two-step thermal reflow processes, they are 130 °C/3 min and 140 °C/30 s, respectively. As shown in Figure 5, it’s the curved BCE structure measured by the Bruker Stylus Profiler (Dektak XT), which is based on the digital mask patterns designed above. The asymmetry of measurement profile resulted from the shortage of Stylus Profiler in measuring the curved BCE microstructures, which is difficult to guarantee that the stylus can be been through the centerline of each of ommatidia. But it can be seen that the curved BCE structure has a good consistency and each of ommatidium is uniformly distributed on the hemispherical substrate, on the whole. Moreover, in order to further verify the effectiveness of this method, the curved BCE structure with hexagonal ommatidium shape was also successfully fabricated based on a clever design of digital masks graphics, as shown in Figure 6.

4. Conclusion

In summary, we have successfully demonstrated the optimization method for the fabrication of curved BCE array with a simple process route. By this method, BCE array structure with curved substrate can be obtained conveniently and precisely. Results show that the height and diameter of spherical substrate in curved BCE structure can be designed properly by the study of edge bulge effect. By the multi-layer coating method, the uniformity and thickness of photoresist layers can be guaranteed effectively. Based on the DMD maskless lithography technology, the Poor Man’s approach is introduced to study the relationship of exposure and development processes, which can decrease the contour errors well. By the final two-step thermal reflow processes, a well-formed BCE structure with curved substrate can be simply fabricated. This kind of process optimization route method may provide a promising way for curved BCE structure fabrication for its advantages of simple operation and low cost, which is expected to be widely used in security cameras, bionic medicine and other fields.

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