High fill-factor paraboloidal microlens arrays

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I. Introduction

Recently, optical MEMS and flat-panel display systems require microlens arrays (MLAs) to couple the light from light sources to photodetectors effectively and to enhance the characteristics of backlight systems, respectively [1-2]. Also, a high fill-factor MLA is necessary to reduce dead areas between microlenses on CMOS image sensors [3].

According to the applications of MLAs, various profiles of the microlenses are required. But it is hard to control the profile of the microlens using conventional fabrication technologies such as photoresist reflow [4-5], microjet technology [6], and polymeric micromolding of isotropically etched substrates [7], which can only produce spherical curvatures. Furthermore, the numerical aperture value is as small as around 0.1 due to their low aspect ratios. Also, a low fill-factor of the MLAs fabricated by the conventional methods results in a dead area between microlenses in the image sensors and hot spots on the screen in the backlight systems.

In this paper, we proposed a new fabrication method for a high fill-factor MLA with controllable paraboloidal profiles, based upon the 3-D diffuser lithography and additional flood exposure method. Formerly, we reported plastic MLAs with various spherical profiles using the 3-D diffuser lithography only [8-9].

II. Fabrication of MLA

The proposed fabrication method of the MLA consists of three steps as shown in Fig. 1; formation of a high fill-factor photoresist mold using the 3-D diffuser lithography and MESD technology, fabrication of a copper intermediate mold and nickel master mold by electroplating, and plastic replication from the nickel master mold. During the 1st UV exposure step, the UV exposure of 4500 mJ/cm^2 on 80 μm-thick AZ9260® positive photoresist (Clariant Co. Ltd.) was performed through a sandblasted diffuser plate (F43-725; Edmund Optics Co. Ltd.) and photomask (Fig. 1(a)). The 2nd UV exposure was performed without a photomask and diffuser. We adjusted the 2nd exposure dose from 25 mJ/cm^2 to 150 mJ/cm^2 to achieve aspect ratios of the microlens mold from 1.0 to 2.1, respectively (Fig. 1(b)). Then, the multi-exposed regions were removed in a single development step (Fig. 1(c)) [10]. Because the exposed regions of the adjacent microlens patterns overlapped each other, sharp edges between the microlens molds were formed. The radius of the curvature of the sharp apex and the surface root-mean-square (RMS) roughness of the photoresist mold were measured as 100 nm and 2.22 nm, respectively.

Although the photoresist mold could be used as a master for the plastic replication, it was not suitable for repeated replication due to its fragility and degradation during the replication process. Instead, a rigid nickel master mold was developed for the plastic replication. A 300 nm-thick copper seed layer was thermally evaporated on the photoresist mold and the copper mold was electroplated up to 30 μm (1200 mA, 2 hours, Fig. 1(d)). The photoresist mold was subsequently removed with acetone. After an anti-adhesion pretreatment of the copper surface, the nickel master mold was formed by electroplating (1500 mA, 2 hours) and its thickness was 35 μm (Fig. 1(e)). During the replication process, the surface roughness of the nickel master mold was not degraded compared with that of the photoresist mold and its RMS value was measured to be 2.26 nm. Since the nickel master was a positive replica of the photoresist mold, positive-relief MLA patterns could be obtained from the plastic replication of the nickel master mold.

Finally, a UV-curable polymer (refractive index: 1.56; CCTech, Inc.) was poured onto the nickel master mold and covered with a polycarbonate plate. We exposed 1300 mJ/cm^2 of UV light for curing and separated the solidified polymer MLA from the master mold (Fig. 1(f)).

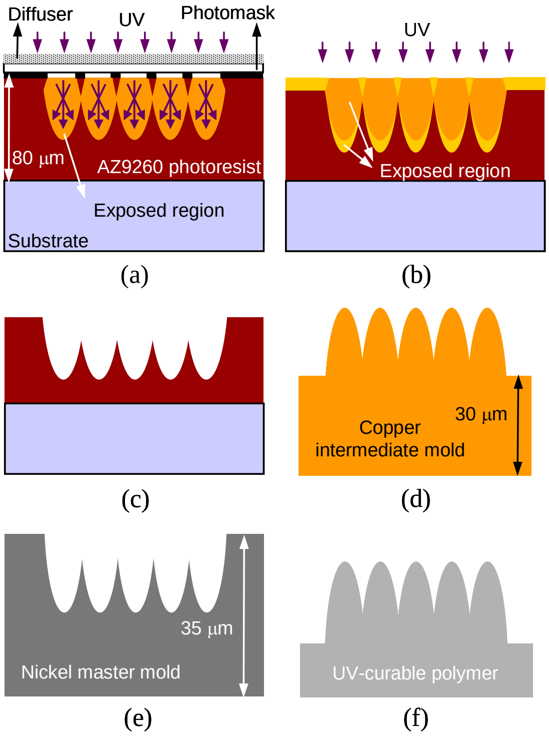

Fig. 1. Fabrication process of an MLA: (a) the 1st UV exposure on the photoresist through a diffuser and photomask, (b) the 2nd UV flood exposure, (c) fabricated photoresist mold after development, (d) fabrication of a copper intermediate mold and (e) a nickel master mold by electroplating, and (f) plastic replication from the nickel master mold.

III. Results and Discussion

Fig. 2 shows the scanning electron microscopy (SEM) photographs of the fabricated plastic MLAs with various heights from 10 μm to 21 μm. The pitch of the MLA was 10 μm, and the microlenses were arranged in a hexagonal array; the area of the MLA was 1 cm by 1 cm. The bird's eye view in Fig. 2(e) shows a uniform and defect-free MLA. The gap between the plastic microlenses increased to 400 nm during the several replication steps. However, the fill-factor of the MLA remained at more than 92 % and it can be improved further by the optimization of the replication processes.

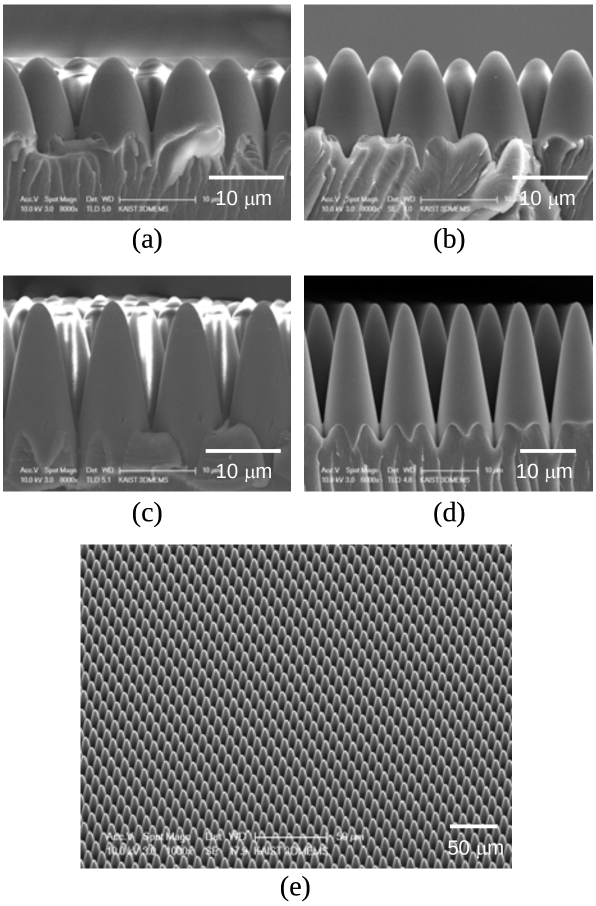

Fig. 2. SEM photographs of the fabricated plastic MLAs with a pitch of 10 μm and various heights of (a) 10 μm, (b) 12 μm, (c) 17 μm, and (d) 21 μm. (e) Bird's eye view of the MLA with a height of 21 μm.

In general, the profile of the microlens is modeled as:

$$h(r) = \frac{1}{R}\frac{r^2}{\sqrt{1+\left(1-(K+1)r^2/R^2\right)}}, \quad (1)$$

where h is the height of the microlens, $r = \left(x^2 + y^2\right)^{1/2}$ is the distance from the curvature to the optical axis, R is the radius of the curvature at the vertex, and K is the aspherical constant [11]. r can be replaced with x for a 2-D profile of the microlens by setting y=0. Assuming a parabolic curvature, K= –1 can be used. As a result, the parabolic profile can be expressed as:

$$h(x) = -\frac{1}{2R}x^2 + h_m, \quad (2)$$

where h_m is the maximum height of the microlens. The minus sign was added to present the positive-relief profile of the microlens.

Comparisons between the actual profiles of the fabricated microlenses and the ideal parabolic profiles were performed, as shown in Fig. 3 (square dots and solid lines, respectively). The profiles of the fabricated microlenses fit very well with the ideal parabolic profiles. Although the RMS error between the actual and the ideal profiles increased to 0.5 μm for the microlens with an aspect ratio over 1.7, the error might be reduced by taking the high order terms of the parabolic profile formula into consideration.

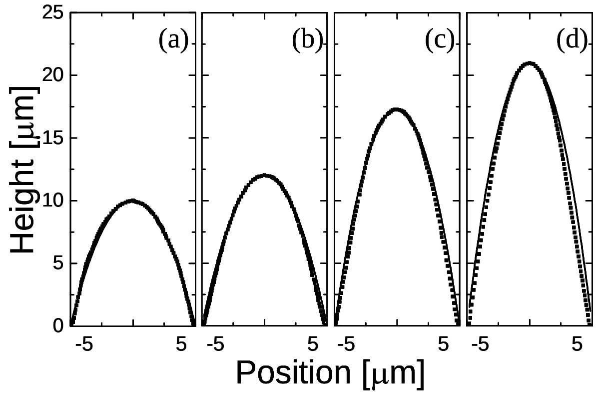

Fig. 3. The actual profile of the fabricated microlens (square dots) and the ideal parabolic profiles (solid lines) with different aspect ratios of (a) 1.0, (b) 1.2, (c) 1.7, and (d) 2.1.

IV. Conclusion

To summarize, a fabrication method for a high fill-factor MLA with paraboloidal profiles was proposed. By adjusting the 2nd UV flood exposure dose, the paraboloidal shape of the microlenses could be controlled. UV-curable polymer MLAs were replicated from the nickel master mold and their profiles fit very well with ideal parabolic curves. The MLAs may be useful for backlight systems of flat-panel displays and other applications that require various profiles and optical characteristics in MLAs.

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