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Camera Imaging Lens Fabrication using Wafer-Scale UV Embossing Process

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We have developed a compact and cost-effective camera module on the basis of wafer-scale-replica processing. A multiple-layered structure of several aspheric lenses in a mobile-phone camera module is first assembled by bonding multiple glass-wafers on which 2-dimensional replica arrays of identical aspheric lenses are UV-embossed, followed by dicing the stacked wafers and packaging them with image sensor chips. This wafer-scale processing leads to at least 95% yield in mass-production, and potentially to a very slim phone with camera-module less than 2 mm in thickness. We have demonstrated a VGA camera module fabricated by the wafer-scale-replica processing with various UV-curable polymers having refractive indices between 1.4 and 1.6, and with three different glass-wafers of which both surfaces are embossed as aspheric lenses having 230 μm sag-height and aspheric-coefficients of lens polynomials up to tenth-order. We have found that precise compensation in material shrinkage of the polymer materials is one of the most technical challenges, in orderto achieve a higher resolution in wafer-scaled lenses for mobile-phone camera modules.

OCIS codes : 160.4670, 220.3630, 220.4610

I. INTRODUCTION

Current trends in mobile-phone evolution may be classified into following two main streams: One is to aim for a high value-added product by embedding multimedia, such as games, MP3, DMB, and Bluetooth, and by improving camera functions, such as higher image-resolution, focus automation, and optical zooming. The other is to highlight its portability by reducing thickness. Samsung Electronics and Motorola lead competition in the market of slim mobile-phones, and some other companies become competitors with their very slender phones.

A promising approach to further reduce the thickness of a mobile-phone is to implement a very thin camera module with thickness comparable to that of a display panel, so as to design a new arrangement of the camera module at the rim of the display panel. Conventional assembly of camera module shown in Fig. 1 (a), which consists of several discrete lenses precisely mounted into a barrel, however, have a limit for reducing the camera-module thickness down under the dimension of the sensor's image format, about 3~4 mm for a VGA camera, for example. Also such a mechanical assembly process requires adjusting for best alignment between lenses while stacking them in a barrel one-by-one, resulting in jamming in mass production.

In this paper, we present a compact and cost-effective camera module fabricated by wafer-scale replication and packaging processes. Schematic of a wafer-scale processed

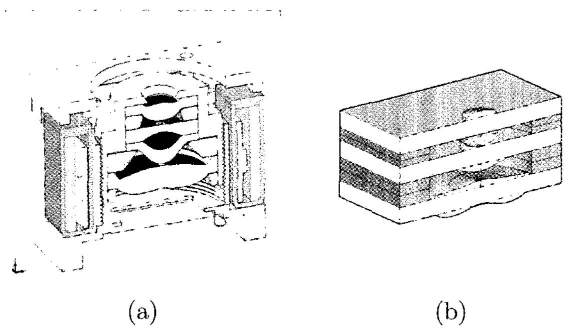

(a) (b)

FIG. 1. Camera modules. (a) Mechanically assembled lenses used in most of current mobile-phones. (b) Wafer-scale packaged lenses in a compact module.

camera-module is shown in Fig. 1 (b), where all of the lenses are glued together rigidly without use of any barrel or mechanical mounts. The wafer-scale processing enables us to get at least 95% yield in mass-production and potentially to realize an ultra-slim camera-module with thickness less than 2 mm. We have demonstrated a VGA camera module fabricated in wafer scale. We have found that surface treatment of polymer, for detaching wide-area wafers replicated from a mold, and precise compensation in material shrinkage of replica materials are the most difficult technical challenges, in order to achieve a designed imaging quality of wafer-scaled lenses for mobile-phone camera modules.

II. CONCEPT OF WAFER-SCALE REPLICATION PROCESS

Replication processes finds various applications such as micro-lens arrays, diffractive optical elements, and nano-imprinting lithography. It can be broadly classified into hot embossing [1] and UV embossing [2]. While hot embossing has difficulty in equipment setup such as wafer aligning stages and zooming microscope since it cures resin by controlling temperature at high pressure, the UV embossing process, using UV light for curing at low temperature and low pressure, is much easier for aligning transparent glass wafers [3-6]. Additionally, refractive indices of UV-curable polymers can be easily controlled within the range between 1.4 and 1.6, which gives lens designers significant freedom in material selections. In this study, a UV embossing technique was applied in fabrication of wafer-scale replica lenses.

Each of the lenses to be stacked layer-on-layer in a camera module is first duplicated many times on a glass wafer by UV embossing, and then assembled by bonding the glass-wafers on which 2-D replica arrays of identical aspheric lenses are UV embossed, followed by dicing the stacked wafers and packaging them with image sensor chips.

Fig. 2 shows overall processing steps of the UV-embossing, which is a key fabrication process in the wafer-scale replication. A metal mold created by diamond turning is used in step-(1) to duplicate multiple lenses on the whole area of the glass wafer, resulting in a master template for the next steps. The master is then transferred to a soft (photopolymer) mold at step-(3) after a special surface treatment with an anti-sticking layer at step-(2). The soft mold is used for another UV-embossing process at step-(5) to produce a final wafer replicated with photopolymer materials of proper refractive indices. The whole procedure adopted in this work will be described in the next section by specially focusing our endeavors on releasing and shrinkage-compensating of replicas.

III. DESIGN AND EXPERIMENT

1. Replication procedure

A flow chart of our fabrication experiment from design to image evaluation is presented in Fig. 3. Lens design is carried out for VGA camera modules. This lens module has more than one wafer with double-sided lenses. Maximum diameter is about 3.2 mm and maximum sag is around 230 μm. A diamond turning machine is selected to make metal molds according to the lens design. UV-curable fluorinated acrylate photopolymer is used for mastering resin since it is well known that photopolymer containing fluorine shows good release characteristics and this resin has significantly low shrinkage. In mastering, step-(1) in Fig. 2, each metal mold is filled with the specific amount of liquid resin and aligned to metal align-keys that are deposited on a 4-inch glass substrate for the the master. Exposure with

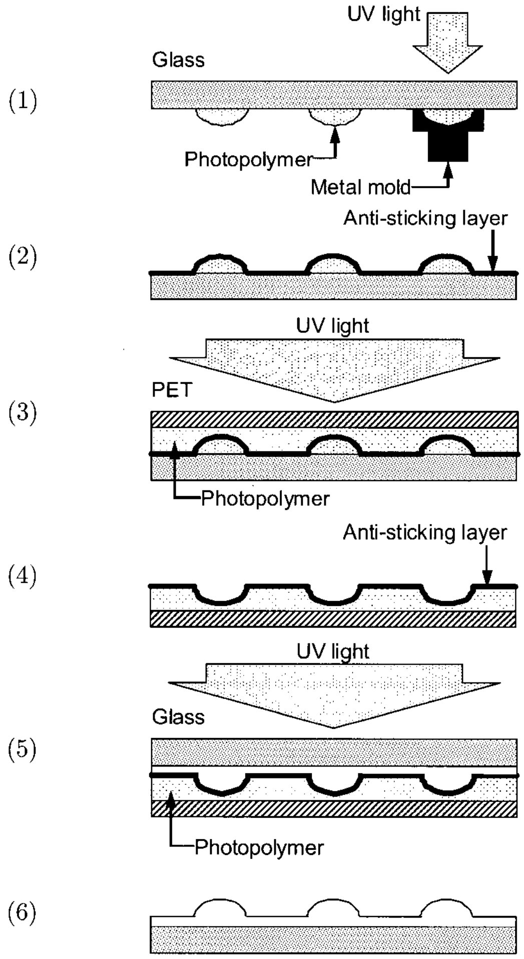


FIG. 2. UV-embossing process. (1) mastering, (2) anti-sticking of master surface, (3) soft molding, (4) anti-sticking of soft-mold surface, (5) lens replication, and (6) final lens-embedding wafer.

UV light through a glass initiates polymerization of mastering resin. The mastering equipment consists of moving stages to align the metal molds, a polymer dispenser, a zooming microscope, a spot type UV exposing equipment, a load cell to control pressure between metal mold and glass wafer.

As shown in Fig. 2 (step-(3)), a transparent PET film that is treated chemically on both sides to improve release characteristics is used as a substrate for soft molding. The same mastering polymer is dispensed to the master and the whole wafer is irradiated with UV. Total UV energy is set to 2500 mJ/cm^2 that is provided by the polymer supplier and represents the value in which the curing curve starts to saturate to the maximum curing level. Our experiments controlled a exposing time and power of UV light to find the optimized curing condition. The step-(5) in Fig. 2 explains how the lens is replicated, which looks similar to soft molding process. Unlike a soft molding lens, on the other hand, the replication process needs alignment to metal keys deposited on the wafer for replicated lens and double-sided fabrication. Moreover, different optical polymers (Chemoptics inc.) are used for specific surfaces according to the lens design. The residual layer remaining after the step-6 must be carefully controlled by pressure the glass plate before UV exposure.

The replicated lens profile is measured by surface profiler (P-15, Tencor). The measured profile data are treated in the MATLAB program which can compare them with other profiles including those of design, a metal mold, master, soft mold, and replicated lens and show differences, shrinkage, between selected profiles. The program also calculates aspherical coefficients for the data, which are used to compensate manufacturing errors in the metal molds.

2. Release process

As shown in Fig. 3, release processes are required to separate the master and the soft mold, and successively, to separate the soft mold and the replicated lens. In general, an anti-adhesion layer is applied on the photopolymer surface to improve release characteristic by decreasing surface energy of polymer. Although polymers containing fluorine, which are used for the master and the soft mold, are known to have good release feature without additional surface treatment, various treatments such as self-assembled monolayers (SAMs) [7], plasma polymerization using hexamethyldisilane (HMDS) [8], and thin metal-film deposition [9] had been tested in order to increase the mold lifetime and to improve smoothness of replicated lens surface. Before applying the treatments, molds were cleaned by O_2 plasma at low RF power and low temperature to remove dust on the polymer surface.

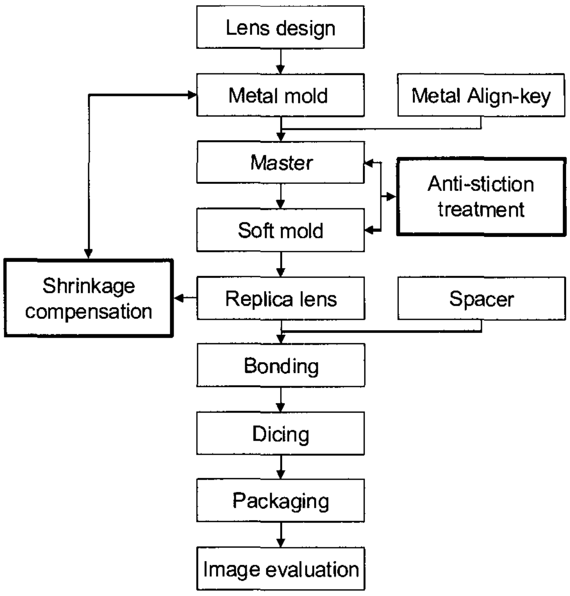


FIG. 3. Design and experimental procedures of wafer-scale lens process.

IV. FABRICATION OF VGA CAMERA MODULES

1. Shrinkage compensation

Polymer resin inevitably undergoes volume shrinkage after the curing process due to the change in concentration by the conversion from C=C bond to C-C bond during the UV exposure. This volume shrinkage can be classified into vertical and horizontal components. In this study, horizontal shrinkage was ignored since the glass substrate is much thicker than the polymer layer, which prevents the polymer layer from shrinking horizontally. The shrinkage of photopolymer materials was defined as the difference in the height $(\triangle H)$ of the lens profile between the designed lens and the replicated lens. Fig. 4 shows an optical image and a 3D profile of a convex lens after the mastering step. These show no recognizable defects such as air bubbles inside the lens and bursts on the lens surface. It was also observed that the horizontal shrinkage was significantly smaller than the vertical one.

Shrinkage of 10~20% compared to the lens design during the whole process was obtained in our replicated lenses, depending on the UV curing conditions such as the UV light power, the exposure time, and the pressure. Various experiments were made to obtain optimal UV-curing conditions to minimize the shrinkage. Fig. 5 shows an example result when the replication was made under these optimal conditions. The center height of the lens is shown to decrease in a sequential order for the designed-, master, soft mold, and replicated lens as shown in Fig. 5 (a). The shrinkage at the center of the resultant lens was ~14.3% ($\triangle H$=32.9 μm), which, compared with that of the designed value, was unexpectedly large. Fig. 5 (b) shows the profile difference over the lens, $\triangle H$, for the replicated lens, which has a symmetrical profile as the designed aspherical lens has circular symmetry. The experimentally obtained polymer-shrinkage results were used to obtain the compensated profile for the metal molds. The modification of metal mold can be easily made with the well-established remaking process.

The necessary profile modification data for the metal mold were obtained from aspherical coefficients of the shrinkage-compensated lens by the difference in profile height ($\triangle H$) between the designed and replicated lens. Fig. 6 (a) shows the results of such shrinkage compensation, showing the evident improvement of the replicated lens profile compared with that of the uncompensated lens. The profile height error and deviation between the designed and shrinkage-compensated replicated lens were -1.8% ($\triangle H$=-4.21 μm) and ±0.33 μm, which show an order of magnitude improvement compared with the uncompensated lens as shown in Fig. 6 (b). The profile height error $\triangle H$ is nearly uniform on the average of -4.21 μm over the lens. This means that a further improvement in replicated lens profile can be achieved by proper shrinkage compensation through the process optimization and additional modification of the metal mold.

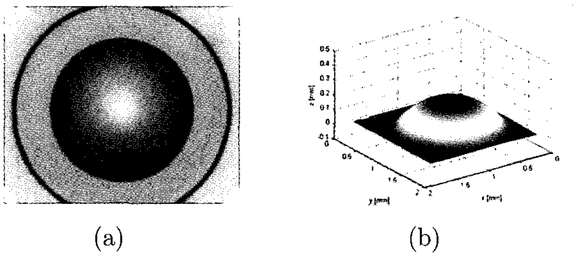
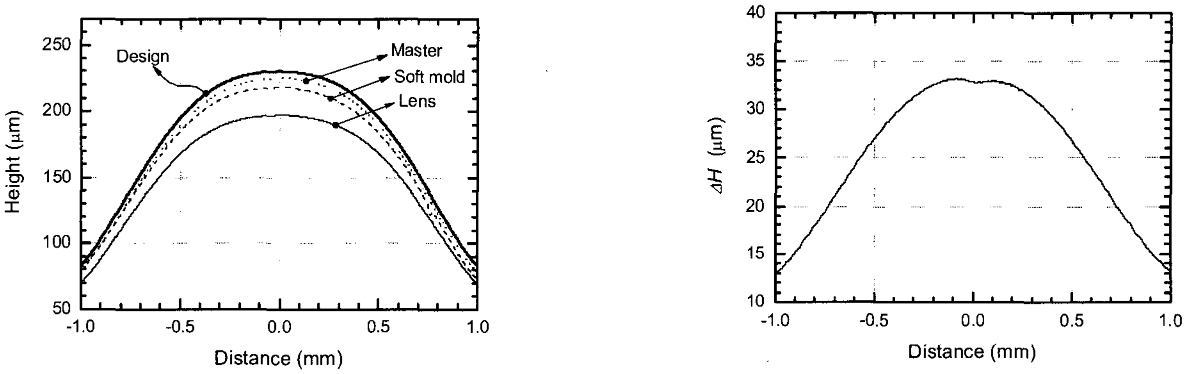


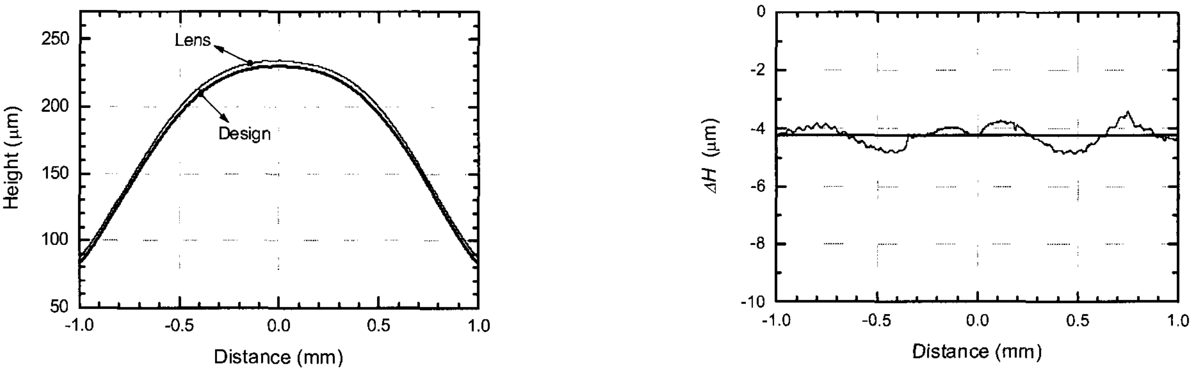
FIG. 4. (a) A microscope image and (b) 3D profile of the mater convex lens.



(a) Profiles of the design (thick), the master (dot), the soft mold (dash), and the replicated lens (thin)

(b) The height difference between profiles of the designed and the replicated lens

FIG. 5. Profiles of the resultant lenses and profiles errors between the designed and the replicated lenses before the shrinkage compensation.



(a) Profiles of the design (thick) and the replicated (thin) lenses

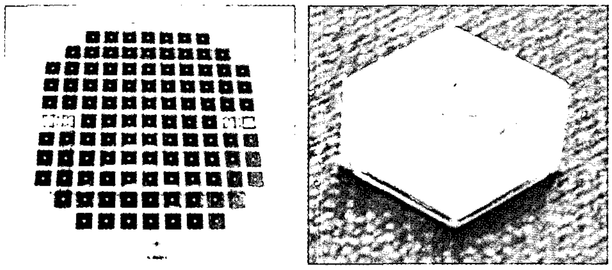
(b) Difference between profiles of the designed-and the shrinkage-compensated replicated lenses

FIG. 6. Lens profiles and profile errors between the designed and the shrinkage-compensated replicated lenses.

2. Packaging of VGA camera modules

A VGA camera module consisting of 3 wafers, each of which having double-sided lenses (total 6 lens surfaces per module), were fabricated. Four-inch glass wafers were used for substrates and reflective indices of optical polymers used for replicated lenses were in the range between 1.4 and 1.6. As shown in Fig. 7, Aluminum thin film was deposited on the first surface of the lens module to form the aperture. Also, IR coating to filter out infrared portion of the spectrum was applied on the final-wafer surface, which makes an additional (separate) IR filtering element unnecessary. Total 105 lenses could be fabricated on a 4-inch wafer where the dimension of the replicated lens was 5.0×5.0 mm^2.

To bond the three wafers into a single module, additional considerations such as align keys, spacers (made of silicon or glass wafers), and wafer-to-spacer bonding method should be carefully addressed [10,11]. After proper use of spacers and dicing, the lens module shown in Fig. 7 was obtained (volume dimension of 5.0×5.0×3.2 mm^3) and was subsequently assembled with an image sensor by using a plastic barrel. Wafer-scale lens-to-lens de-center and the tilt of the fabricated lens module were found to be 2~5 μm and 0.01~0.05°, respectively.



(a) Photograph of the replicated wafer lenses (b) VGA lens unit stacked with 3 wafers

FIG. 7. Image of the wafer-scale lens unit

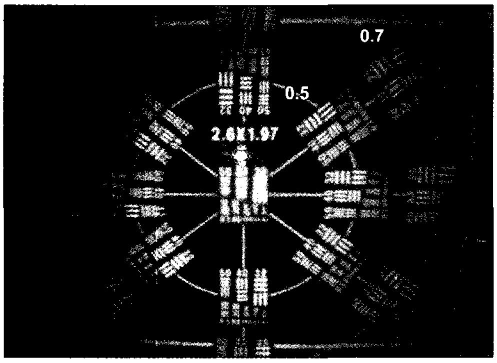


FIG. 8. Photograph of test resolution chart projected on screen through the VGA camera module.

3. Evaluation of VGA camera modules

The VGA camera module was designed to have a resolution of 80 lp/mm at 0.7 fields. Figure 8 shows an image of the test resolution chart projected on the screen through the fabricated VGA camera module. It can be seen from the test image that the lens module has a spatial resolution about ~63 lp/mm at 0.7 fields. The uniformity of resolutions obtained at different wafer positions are fairly good with ~60 lp/mm. The measured resolution is lower than the designed value mainly due to the errors of both profile and thickness of the replicated lens by insufficient shrinkage compensation [12] in metal core and non-zero vertical offset shown in Fig. 6 (b). With proper compensation on all lens surfaces as mentioned above, we are improving the imaging resolution of the camera module and will demonstrate a camera module as it was designed in the near future. In addition to that, we are currently working on improvement of accuracy in processing equipments.

V. CONCLUSIONS

We have introduced a fabrication technique of camera modules by wafer-scale-replica processing, and demonstrated VGA camera modules. The metal mold is modified by the compensation of polymer shrinkage for the replicated lens compared to the design profile. The resultant replicated lens has small shrinkage of about -1.8 % at the center of the lens. The 3-wafers VGA camera module is fabricated and tested by a projector. Furthermore, the improved camera modules are under manufacture by re-modification of metal molds.

We believe that the wafer-scale processing is one of promising approaches to reduce down the thickness of mobile-phones as well as the cost of camera-modules. With the basis of the wafer-scale process, we are currently developing an ultra-slim camera module with its thickness less than 2 mm. Those camera modules without any barrels may give designers new degree of freedom for arrangement of camera modules at the rim of a display panel, even inside the panel.

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