Nanohot embossing using curved stage to replicate antireflection nanostructures onto light guide

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Abstract

A nanohot embossing using a curved stage is proposed to improve the replication ratio of nanostructures at near the edge of a thick (sub-mm-order thickness) polymer substrate. The lower replication ratio at near the edge resulting from a conventional hot embossing is due to lower compressive stress, which is simulated by the finite-element method (FEM). The height of the proposed curved stage is gradually increased from the center to the edge to bring the levels of compressive stress at the center and at the edge closer. Here, we demonstrate replications of antireflection nanostructures, which have both pitch and height of 200 nm, onto the 0.75-mm-thick light guide for the light emitting diode (LED) frontlight systems used in mobile phones. It was found that a cutting depth of 14 \textmu m on the curved stage is necessary to achieve a high uniformity of the replication ratio at near the edge. The replication ratio at near the edge is improved from 65\% to 94\%. The reflectance of the antireflection structures is 0.6\%, which is a high enough quality for use in LED frontlight systems.

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1. Introduction

To reduce the number of optical components in optical devices, optical functions have been integrated into single optical devices. Most importantly, with the rapid miniaturization of mobile phones, optical functions have been integrated into a light guide, which is the main component of LED backlight or frontlight system for illuminating liquid crystal displays (LCDs) [1–4]. A prism sheet or a diffusive sheet has also been integrated into the light guide [5,6]. Additionally, antireflection function is strongly anticipated for improving a contrast ratio of LCD using frontlight system. For this function, technologies utilizing 100-nm-order nanostructures on the surface of devices have been reported [4,7,8].

Nanoimprint lithography (NIL) is a promising approach to pressing a patterned mold into a thin (sub-\mu m-order thickness) polymer layer coated on a hard substrate for fabricating nanostructures [9]. However, in frontlight systems, thick (sub-mm-order thickness) polymer substrates are used. Imprinting nanostructures onto such thick polymer substrates, the so-called nanohot embossing in this study, is difficult to achieve. In the case of the conventional hot embossing, the replication ratio of nanostructures at near the edge of a thick polymer substrate is lower than that at the center, because the polymer at near the edge is pushed out to the side of the substrate and pressure is lost. At the same time, nanohot embossing is expected to find wide application in microelectromechanical system (MEMS) and biomedical areas. And a sub-wavelength nanostructure is expected to realize holographic and polarizer functions.

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The goal of this study is to develop a nanohot embossing for achieving a high replication ratio of nanostructure transfer at near the edge of thick polymer substrates. We propose a nanohot embossing using a curved stage. The height of the curved stage is gradually increased from the center to the edge to increase pressure at the edge. After describing the design of a curved stage, this paper describes fabrications of antireflection nanostructures onto light guide. Experimental results of the fabricated antireflection nanostructures are presented and discussed.

2. Design of curved stage

Figs. 1 and 2 show schematic views of NIL and a conventional hot embossing, respectively. In NIL, a mold on an upper stage and a thin polymer layer coated onto a hard substrate on a lower stage are brought into contact, and pressure and temperature are applied. After cooling, the polymer is separated from the mold with the reversed nanostructures imprinted.

In the conventional hot embossing, a thick polymer substrate without hard substrates is placed on the lower stage. The other processes are the same as those of NIL.

Fig. 1. Schematic views of NIL: (a) construction and (b) close-up view.

Fig. 2. Schematic views of conventional hot embossing: (a) construction and (b) close up view.

Fig. 3. Images of equivalent stress distribution simulated by FEM: (a) NIL and (b) conventional hot embossing.
antireflection function into the light guides for the LED frontlight systems used in mobile phones in order to improve the contrast ratio of LCDs [5]. An antireflection nanostructure has sub-wavelength grating on the surface of the polymer. The pitch of the sub-wavelength grating must be less than the wavelength of the incident light. Only 0th-order diffraction light is generated by the sub-wavelength grating. In this case, in a direction toward a polymer substrate, the volume of the sub-wavelength grating increases gradually, and an effective refractive index of sub-wavelength grating changes gradually from the refractive index of the material on the sub-wavelength grating to that of the sub-wavelength grating. In the case of this study, the antireflection nanostructure is made of COP, which contacts air. The incident light to the antireflection nanostructures is not reflected at the interface between air and polymer because its effective refractive index changes gradually from the refractive index of air (1.00) to that of COP (1.53) due to the antireflection nanostructures. The reflectance of antireflection nanostructures depends on the height of nanostructures. For lowering the reflectance, the change of the effective refractive index must be gentle. Therefore, the height of nanostructures must be higher. Both the pitch and height of the antireflection nanostructures were designed to be 200 nm [7].

The master pattern of antireflection nanostructures was fabricated by electron beam lithography [10]. We used a silicon wafer with a positive resist (AR-P 619, Allresist) spin coated to a thickness of 2 μm with an e-beam machine (ELS3300, Elionix). Before fabricating antireflection nanostructures, the resist sensitivity curve, which is a characteristic of the residual resist thickness dependence on the electron dose, was obtained. For this purpose, a test pattern was fabricated on a silicon wafer with the resist layer to a thickness of 2 μm and an Au layer to a thickness of 20 nm; the electron dose varied from 10 to 100 μC/cm² at 5 μC/cm² steps. After exposure, the Au layer was dissolved and the exposed pattern was developed. The resist sensitivity curve was obtained by measuring the residual resist thickness. Antireflection nanostructures were fabricated by the above-mentioned process, and antireflection nanostructures’ shape was controlled by exposure energy determined by this resist sensitivity curve. The replication mold was fabricated by nickel electroplating on the master pattern. Scanning electron microscope (SEM) image of

![Fig. 4. Compressive stress distribution simulated by FEM.](image)

![Fig. 5. Schematic view of nanohot embossing with curved surface: (a) construction, (b) cross-section view of diagonal line and (c) top view.](image)
nanostructures on the electroplated nickel mold is shown in Fig. 6.

Both the curved stage and the lower stage were made of brass and were fabricated by the machining method. Five curved stages were fabricated with cutting depths $C$ of 0 μm (conventional upper stage), 7, 14, 28 and 42 μm. Curved stages were spherical surfaces. The size of stages $X$ and $Y$ (in Fig. 5) were 34 × 46 mm. The lower stage surface was flat.

Fig. 7(a) shows the hot embossing equipment used in this study. It consists mainly of the curved stage, the mold with nanostructures on the curved stage, and the lower stage. Heaters are set in both the upper and lower stages. A close-up view of the equipment is shown in Fig. 7(b). The equipment has a force-loading capacity of 2500 kg and a limitation temperature of 350 °C.

The thickness of the polymer substrate and the pattern area is 0.75 mm, corresponding to the common thickness of light guides, and its size is 32 × 44 mm, corresponding to a typical mobile phone’s display area, respectively. The thick polymer substrate was made of COP. COP is used for fabricating typical light guides for frontlight systems.

In our hot embossing, the mold on the upper stage is heated above $T_g$ of the COP. The mold and the thick substrate on the lower stage are brought into contact. Pressure is applied between the mold and the substrate to press the polymer into the mold completely. Then, the pressure is lowered and the polymer cooled below $T_g$. The substrate is separated from the mold with the reversed nanostructures imprinted onto the polymer substrate.

There are two significant difficulties in nanohot embossing the nanostructures onto the entire thick polymer substrate: (1) filling the polymer at near the edge of the substrate into the mold’s nanostructures fully and (2) keeping the shape of the thick substrate without melting the light guide. An effective method of filling the polymer into the nanostructure on the mold is to increase the thermal energy. To preserve the shape of the light guide, the thermal energy supplied to the substrate is limited. To limit the thermal energy, the temperature of the lower stage with the substrate is set at 130 °C, which is lower than $T_g$, and the temperature of the curved stage with the mold is set at 160 °C, which is higher than $T_g$. The embossing time is set at 10 s. Under this condition, when the temperature increases above $T_g$, this time is shortened.

The replication ratio at the center of the thick polymer substrates versus applied pressure is shown in Fig. 8. Complete replications were realized above 5 MPa. However, at a pressure above 10 MPa, the shape of the substrate is not maintained, because the pressure at near the edge with this condition was high.

Replication ratio at near the edge, which is defined as distance of 2 mm from the corner of the substrate (in Fig. 5), of the thick polymer substrate with pressure of
5 MPa versus cutting depth $C$ of the curved stage is shown in Fig. 9. Above a cutting depth $C$ of 14 $\mu$m, the replication ratio is improved. But above $C$ of 28 $\mu$m, the shape of the substrate is not maintained, because the pressure at near the edge with this condition was high. SEM images of antireflection structures by stages of $C = 0$ (conventional hot embossing) and $C = 14 \mu$m at near the edge are shown in Fig. 10. The replication ratio at near the edge is improved from 65% to 94%. A high uniformity of the replication ratio could be achieved while maintaining the shape of the substrate by using the curved stage with $C = 14 \mu$m.

The reflectance of antireflection nanostructures at near the edge was then measured. Reflectance produced by the conventional hot embossing and that by the nanohot embossing using curved stage were 1.5% and 0.6%, respectively. The reason for improvement of the reflectance is that the replication ratio was improved by using the curve stage and height of antireflection nanostructures near the design height. The reflectance achieved by the new method is sufficient for use in LED frontlight systems.

4. Conclusions

With the conventional hot embossing, the replication ratio of nanostructures at the edge of a thick (sub-mm-order thickness) polymer substrate is low. This is because the polymer at near the edge is pushed out to the side and a loss of pressure occurs. The stress distribution is simulated by the FEM. The compressive stress at near the edge of a thick polymer substrate is lower than that at the center. This lower stress causes a lower replication ratio at near the edge. To solve this problem, we proposed a nanohot embossing using a curved stage. The height of the curved stage is gradually increased from the center to the edge of the spherical surface to bring the levels of compressive stress at the center and the edge closer.

We have demonstrated the replications of antireflection nanostructures onto light guides that are 0.75 mm thick and made of COP for the LED frontlight systems used in mobile phones in order to improve the contrast ratio of LCDs. The pitch and height of the antireflection structures were 200 nm. The mold of the antireflection nanostructure was fabricated by the nickel electroplating method. Consequently, the cutting depth of the curved stage must be 14 $\mu$m to achieve a high uniformity of the replication ratio. The replication ratio at near the edge was improved.
from 65% to 94%. Furthermore, the reflectance of antireflection structures at near the edge was 0.6%, which provides sufficient quality for use in LED frontlight systems.

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