High quality Bragg gratings fabricated by Nanoimprint Lithography

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Abstract. Nanoimprint lithography (NIL) is a very promising technology for nanostructure fabrication, because of its high resolution, low cost and high throughput. In this paper, we have demonstrated high-resolution rectangular Bragg gratings for DFB LD by NIL technology. For the manufacture of high quality gratings, the stamp types and residual resist thickness are discussed, and an improved Simultaneous Thermal and UV (STU) imprint process with temperature-pressure variation is introduced.

1. Introduction
With narrow linewidth, high side mode suppression ration (SMSR) and wavelength stability, distributed feedback laser diodes (DFB LD) have been widely adopted in optical communication networks. Efforts to reduce cost of the device and simply its fabrication process have been continued since it invented. Besides epitaxial process, performances of the devices are mainly depended on the quality of embedded waveguide Bragg gratings. Normally, there are two methods for fabricating waveguide Bragg gratings, interference exposure, electron beam lithography (EBL). Interference exposure can be used to perform uniform gratings, but not suitable to fabricate phase-shifted gratings. Electron-beam lithography (EBL) has sufficient resolution and the capability to fabricate irregular patterns, but it suffers from high cost and low throughput, which prevents this method from mass production. Nanoimprint lithography (NIL) [1] has been introduced in DFB fabrication as a new method to perform gratings with good manufacture quality [2]-[3], low cost and high throughput. Compared with conventional lithographic approaches, which define the patterns by using either photons or electrons to modify the properties of the photoresist, NIL is based on the mechanical embossing principle.

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It relies on direct mechanical deformation of the resist, and therefore can achieve high pattern resolutions beyond the limitations set by light diffractions or beam scattering. Actually, the pattern resolutions during the process are mainly limited by the stamp. NIL has the capability of patterning sub 10 nm features [4]-[5].

In order to enhance the fault tolerance capability for unexpected defects, such as particles or unflatness on the substrate, achieve large area, high uniformity imprint result and avoid damages to the stamp or substrate, usually, soft press process [6]-[7] with an flexible intermediate polymer stamp is introduced. The imprint process is shown in Figure 1.

For NIL technology, the stamps are usually made of some durable hard materials, such as silicon and silica, and the patterns on the stamps are usually of two types, positive and negative. For the first type, the top surface of the pattern is higher than the areas with no patterns, the patterns are anaglyphic; however, the negative patterns are invaginated into the stamp, they are beneath the stamp surface. These two types are both widely used in NIL technology, in this paper, experiments are carried out to make a comparison to find out the very type which is more suitable for NIL technology.

In addition, with the consideration of preventing the stamp and substrate from mechanical damages, stamp will not contact with the substrate during the imprint process, illustrated in Figure 1(b), they are separated by some residual resist. Too thick residual resist will hamper subsequent pattern etching process, as when the residual resist is removed by reactive ion etching (RIE) process, the pattern mask will be degraded. Continual efforts [8]-[9] have been trying to thin the residual resist, herein, an advanced process with temperature-pressure variation [10]-[11] is introduced.

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**Figure 1.** Schematic diagram process flow of nanoimprint with an intermediate polymer stamp: (a) fabrication of a polymer stamp, (b) imprint with the polymer stamp and STU process.
2. **Experiment**

2.1. **Stamps**

Two fabricated stamps have nearly the same patterns, are both Bragg gratings for DFB LDs, however, one stamp is negative, the other is positive. On the stamps, there is a Bragg grating structure for one DFB LD in each $250 \times 250 \ \mu m^2$ area. The gratings have the same period, and the depth of the negative patterns is about 124-130 nm, however, the height of the gratings is 60 nm on the positive stamp. Before the imprint process, an anti-adhesion layer coating is deposited on the stamps by immersing them in a tridecafluoro-1, 1, 2, 2-tetrahydrooctyl trichlorosilane (TFS) [12] solution.

To compare these two stamps, in this experiment their patterns are transferred onto intermediate polymer stamps first, secondly, polymer stamps are imprinted on thick resist with the process shown in Figure 2(a), imprint time varies from 1 to 30 minutes, and then the pattern quality is inspected by AFM (Veeco NanoScope MultiMode) and SEM (Quanta 200), the yield is computed under Olympus BX51 optical microscope.

![Figure 2. Schematic illustrations of (a) conventional NIL process and (b) NIL process with temperature-pressure variations](image)

2.2. **Residual resist**

During the imprint process, to ensure full filling of the stamp and prevent the stamp or substrate from damages, the resist should have sufficient thickness, normally, the thicker the resist, the better the pattern quality. However, with the consideration of subsequent pattern transfer process, the resist should be as thin as enough to guarantee a thin layer of residual resist. Compared with conventional process, in this study we introduce an improved NIL process, shown in Figure 2(b), to obtain a very thin residual resist layer, and ensure good imprinted pattern quality at the same time.

The viscoelastic properties of the resist has been studied [13], and the relationship between temperature, pressure and the fractional free volume of the resist can be expressed in

\[
f = f_g + \alpha (T - T_g) + \beta (P - P_g)
\]

(1)
Where $f$ is fractional free volume at temperature $T$ and pressure $P$, $f_g$ represents fractional free volume at glass transition and demold pressure, $\alpha$ indicates the thermal expansion coefficient and $\beta$ is compressibility coefficient. As shown in Figure 2(b), with the variations of the temperature and pressure, the fluidity and filling ability of the resist can be enhanced, thus thickness of the resist that needed during the imprint process can be thinned, and the residual resist thickness is reduced. Additionally, at the both ends of the process, the step variation of the pressure can reduce the distortion of the polymer stamp that may induced by large sudden pressure variations.

In this experiment, we compared the improved NIL process with a conventional one, the imprint time of the latter process is 3 minutes. The negative Bragg grating stamp is employed. The thickness of spun resist is varied from 110 nm to 160 nm, with 10 nm as an interval.

3. Results and Discussions

3.1. Stamps

![Microscope image of large area imprinted gratings](image1.png) ![AFM 2D image of Bragg grating structure](image2.png)

**Figure 3.** (a) Microscope image of large area imprinted gratings, (b) AFM 2D image of Bragg grating structure. The stamp is negative, and the imprint time is 3 minutes.

As shown in the results illustrated in Figure 3, the negative stamp is easy to be filled by the resist, very good grating quality and high yield (higher than 80%) can be obtained in only 3 minutes. However, when it comes to the positive stamp, though the height of the patterns is nearly one half of the patterns in negative stamp, the filling behavior is very slow, indicated by Figure 4(a)-(c), the grating patterns can not be fully filled within 10 minutes, actually from Figure 4(d), it takes nearly 30 minutes to ensure a complete filling.
Figure 4. AFM images of imprint results under different time with positive stamp: (a) 3 min, (b) 5 min, (c) 10 min and (d) 30 min.

3.2. Residual resist
Figure 5. Microscope images of large area gratings imprinted with varied resist thickness: (a) 120 nm, (b) 130 nm, (c) 140 nm and (d) 160 nm. The negative stamp is imprinted with conventional process, and the imprint time is 3 min.

Figure 6. Microscope images of large area gratings imprinted with varied resist thickness: (a) 110 nm, (b) 120 nm, (c) 130 nm and (d) 140 nm. The negative stamp is imprinted with improved process with temperature-pressure variations.
Shown in Figure 5 and Figure 7, when imprinted with conventional process, to obtain a good pattern quality and high yield, the resist should be thicker than 150 nm, which means the residual resist thickness is nearly 30 nm. For the improved process, illustrated in Figure 7 and Figure 7, nevertheless, despite the resist thickness is only 130 nm, the imprinted grating is already uniform and straight, the yield is higher than 90%. With the residual resist thinner than 10 nm, patterns can be easily transferred to the substrate by a reactive ion etching (RIE) process with high quality, shown in Figure 8. This result is owning to the temperature-pressure variations during the NIL process, which enhance the fluidity and filling effects of the resist, then the necessary resist thickness can be reduced, and so do the residual resist.

4. Conclusions

In this paper, quality of Bragg gratings fabricated by Nanoimprint Lithography are studied, with a focus on NIL stamp and residual resist thickness From the results, compared with positive stamps, negative ones are easier to be filled, the imprint time can be very short, consequently, negative stamps are more suitable for soft NIL process. In addition, an improved NIL process is introduced, the temperature-pressure variations can enhance the fluidity and filling effects of the resist, then reduce the necessary resist and subsequent
residual resist thickness. With a layer of residual resist thinner than 10 nm, high quality rectangular Bragg gratings are transferred onto substrates by a reactive ion etching (RIE) process.

References
[1] Chou S Y, Krauss P R and Renstrom P J 1995 Appl. Phys. Lett. 67 3114.
[2] Yanagisawa M, Tsuji Y, Yoshinaga H, Kono N and Hiratsuta K 2009 Japan. J. Appl. Phys. 48 06FH11.
[3] Wang L, Zhang Y W, Qiu F, Zhou N, Wang D L, Xu Z M, Zhao Y L, Yu Y L and Liu W 2010 Front. Opto. China 3 1674.
[4] Chou S Y, Krauss P R, Zhang W, Guo L J and Zhuang L 1997 J.V.S.Technol.B 15 2897-2904.
[5] Schwartzman M and Wind S J 2009 Nano Lett. 9 3629-3634.
[6] Gao H, Tan H, Zhang W, Morton K and Chou S Y 2006 Nano Lett. 6 2438-2441.
[7] Obducat AB USA Patent US 7082876.
[8] Cheng X and Guo L J 2004 Micro. Engineering 71 177-282.
[9] Liao W-C and Hsu S L-C 2007 Nanotechnology 18 065303.
[10] Park H S, Shin H H, Sung M Y, Choi W B, Choi S W and Park S Y 2007 T. S. Manufacture, 20 13-19.
[11] Wang L, Liu W, Zhang Y W, Qiu F, Wang D L, Zhou N and Xu Z M, 2010 A. Opti. Manu. Test. Tech. 7657.
[12] Beck M, Graczyk M, Maximov I, Sarwe E-L, Ling T G I, Keil M and Montelius L 2002 Micro. Engi. 61-62 441-448.
[13] Ferry J D, Viscoelastic Properties of Polymers, 3rd ed. New York: Wiley, 1980