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An improved approach to fabricate distributed feedback laser based on nanoimprint lithography

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The soft-stamp nanoimprint lithography (NIL) has been widely used to improve the quality and uniformity of the large area substrate. However, the soft-stamp easily deforms due to the high pressure during the manufacture process with subsequently leading to the duplicated pattern distortion. In this paper, an optimized NIL process named by High Pressure Difference (HPD) NIL is proposed to fabricate the distributed feedback (DFB) laser, in which a pressure variation with a high contrast and low absolute value during the process instead of the fixed high pressure is introduced to ameliorate the imprinting quality. Meanwhile, the multi-layer mask is employed to remove the residual resist, and effectively improve the overgrowth quality of the grating and the laser performance.

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Keywords: Semiconductor laser, Nanoimprint, Distributed feedback

1. Introduction

The nanoimprint lithography (NIL) was firstly introduced by Stephen Y Chou et al. in 1995 and then widely used in the micro-nano pattern fabrication [1]. Many researchers have worked on the NIL in order to achieve a high resolution and wider application range. The NIL has been greatly updated from the initial hot-embossing and ultraviolet-NIL [2] to step-and-repeat imprinting (SFIL) [3] and soft-stamp NIL [4, 5] in the past decades. The SFIL can be applied on the non-flat substrate to improve the uniformity of the residual layer [3]. The soft-stamp has the capability to improve the pattern transfer quality because of its flexibility, resulting in a good soft contact with the substrate. Such operation can significantly reduce the incomplete filling defect and avoid the hard contact between mother stamp and substrate [6]. In other words, the soft-stamp imprinting can significantly improve the pattern quality and its large area uniformity.

On the other hand, the distributed feedback lasers (DFB) are widely used in optical fiber communication systems because of its highly reliable and stable single-mode operation. At present, the NIL has already been used in the fabrication of the DFB laser diode (LD) [7-9]. The diffraction grating plays an important role in the laser performance. The grating with high quality can effectively improve the laser performance on the single mode and linewidth. Our team focus on the fabricating of DFB LD gratings for years [7,8], by employing the soft stamp based on simultaneous thermal and ultraviolet (STU)–NIL [10,11]. However, due to the flexibility, the soft-stamp easily deforms due to the high pressure during the imprinting process, which significantly reduces the grating quality. In this paper, an optimized NIL process called high pressure difference (HPD) NIL is proposed, which introduces a pressure variation with a high contrast and low absolute value during the process instead of the fixed high pressure to ameliorate the imprinting quality. Meanwhile, the multi-layer mask is employed to remove the etched residual resist and improve the grating overgrowth quality.

2. Experimental procedure

The grating fabrication process is composed of three steps, including the grating imprinting, etching and residual resist removal. In Fig. 1 the fabrication procedure is shown. Precisely, a 50-nm-thick SiO_2 film is firstly deposited on the substrate by plasma enhanced chemical vapor deposition. Then, a 200-nm-thick uv-curable resist is spin-coated on the SiO_2 film layer. Here, the SiO_2 film is used as the isolation layer between the substrate and uv-curable resist. Finally, the soft stamp based STU-NIL is followed to form the patterns of diffraction grating on the SiO_2 film.

The soft stamp based STU-NIL process is shown in Fig. 1-Fig. 2. More specifically, the first step is, a soft stamp is fabricated by thermal NIL process using hard mother stamp directly (shown in Fig. 1). The second step is, the grating imprinting is performed by the STU NIL process (shown in Fig. 2). In the whole procedure, the soft-stamp is used to improve the pattern transfer quality because of its flexibility and good soft contact with the substrate, and the HPD NIL is used to control the feature of resist. Additionally, the temperature-pressure variation during the whole NIL process is shown in Fig. 3.

Following the grating imprinting, a reactive ion etching (RIE, Oxford instruments Plasmalab system 100) process with O_2 is applied to remove the residual resist until the SiO_2 layer exposed with the pressure being 20mTorr, the radio frequency (RF) power being 80W and the etching rate is about 2nm/s (shown in Fig. 2(d)). Then the formed pattern is used as a mask to transfer patterns from uv-curabled resist to the SiO_2 masks (in Fig. 2(e)). The CHF_3/O_2 mixture gas is used to etch SiO_2, with the pressure being 30mTorr and the RF power being 150W, and the etching rate being about 20nm/min. After that, the inductively coupled plasma RIE (ICP-RIE) process with CH_4/H_2 mixture gas is used to etch the substrate and the transfer pattern from SiO_2 mask to the substrate (in Fig. 2(f)) [12]. Finally, the SiO_2 mask is removed by a wet chemical process using the hydrofluoric (HF) acid.

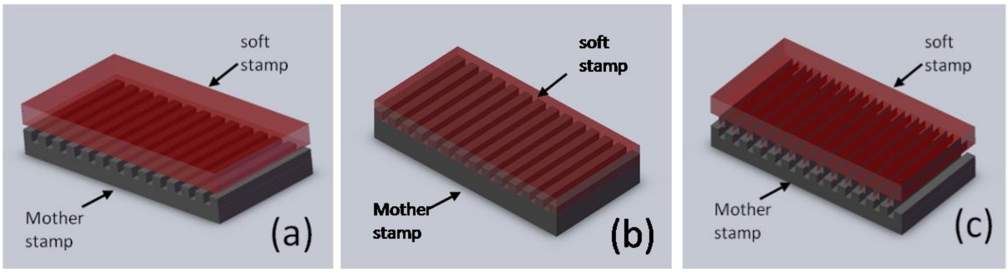

Fig. 1. Fabrication process of soft stamp

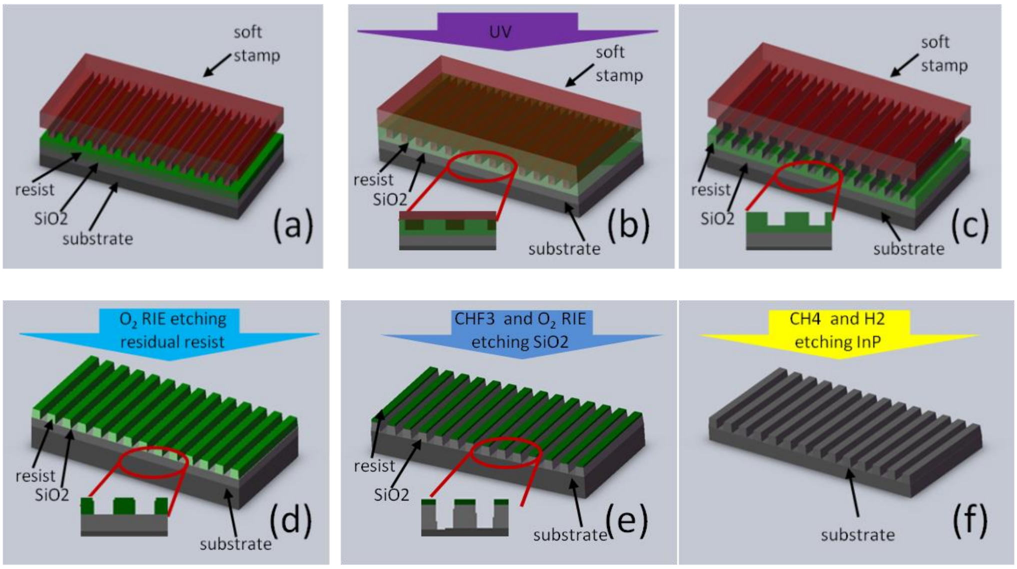

Fig. 2. Fabrication process of gratings

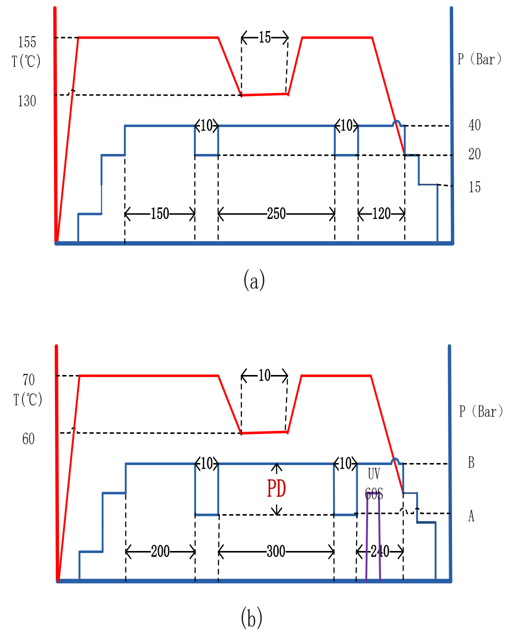

Fig. 3. Temperature-pressure variation imprint process of (a) soft mold fabrication; (b) transferring grating patterns

3. Results and discussions

3.1. The pressure difference (PD) control in grating imprinting process

In the grating transferring process, the pressure control is critical to obtaining the high quality grating and a thin imprinted residual resist layer simultaneously. As known, a high pressure could improve the filling effect and reduce the thickness of the imprinted residual resist [13]. However, due to the flexibility of the soft stamp, the high pressure increases the risk of the soft-stamp deformation and duplicated patterns distortion. The soft-stamp depth is 180 nm in our experiment. Here, the largest high of resist deformation is used to represent the filling degree for the grating.

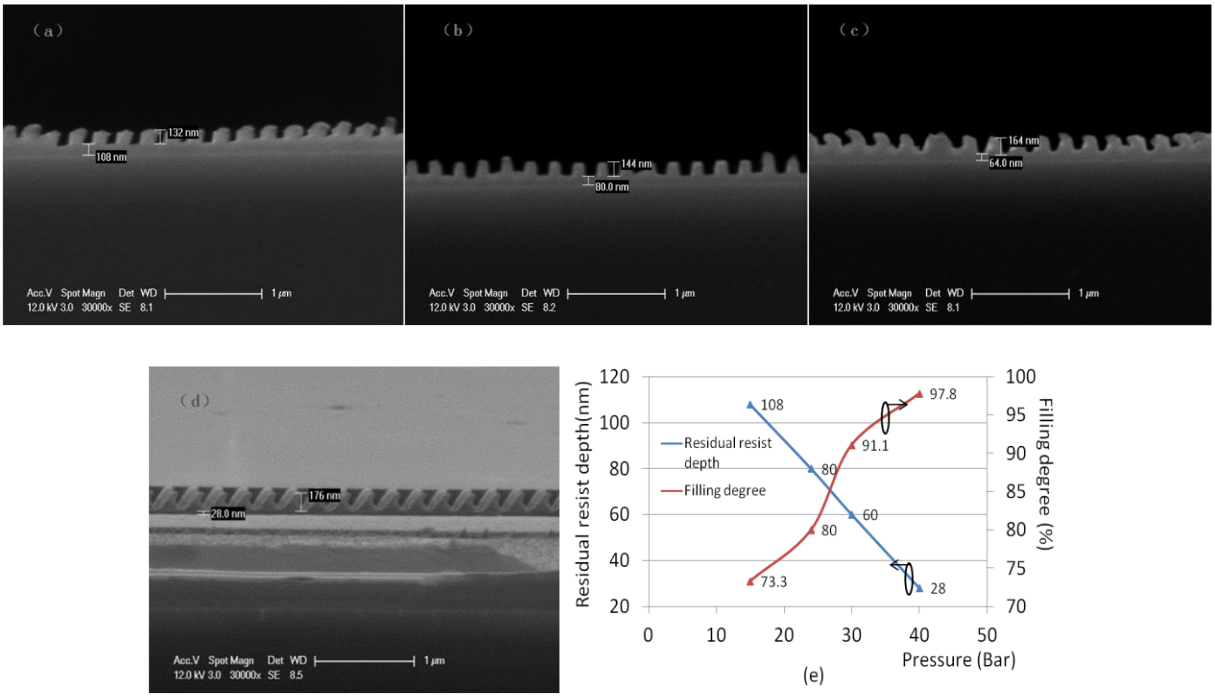

Fig. 4. Grating feature imprinted with different pressure and the same PD (a) P=15Bar, PD =3Bar (b) P=24Bar, PD=3Bar (c) P=30Bar, PD=3Bar (d) P=40Bar, PD=3Bar (e) grating/residual resist depth variation with the pressure at the same PD

As shown in Fig. 4, in the experiment the grating feature varying with the highest pressure is used in the process while the PD stays the same. It can be seen that a low pressure is adverse to resist filling and causes a thicker imprinted residual resist layer, as shown in Fig.4(a). Fig.4(a)-Fig.4(d) show that with the increase of the pressure, the imprinted residual resist layer thickness becomes thinner and thinner. This is because, for a certain volume of resist, a completed grating needs a large volume of resist and so a thin imprinted residual resist can be obtained. However, when the pressure reaches a certain level (in Fig. 4(c)), the soft-stamp deforms, making the grating sloped and the severity increased. Compared with a low pressure, a high pressure increases the risk of pattern distortion although it can improve the filling degree and reduce the thickness of the imprinted residual resist (Fig. 4(e)). To solve this contradiction, the HPD NIL is introduced. Consequently, in the condition of a low pressure, the increase of the PD can improve filling effect and obtain a thin imprinted residual resist layer.

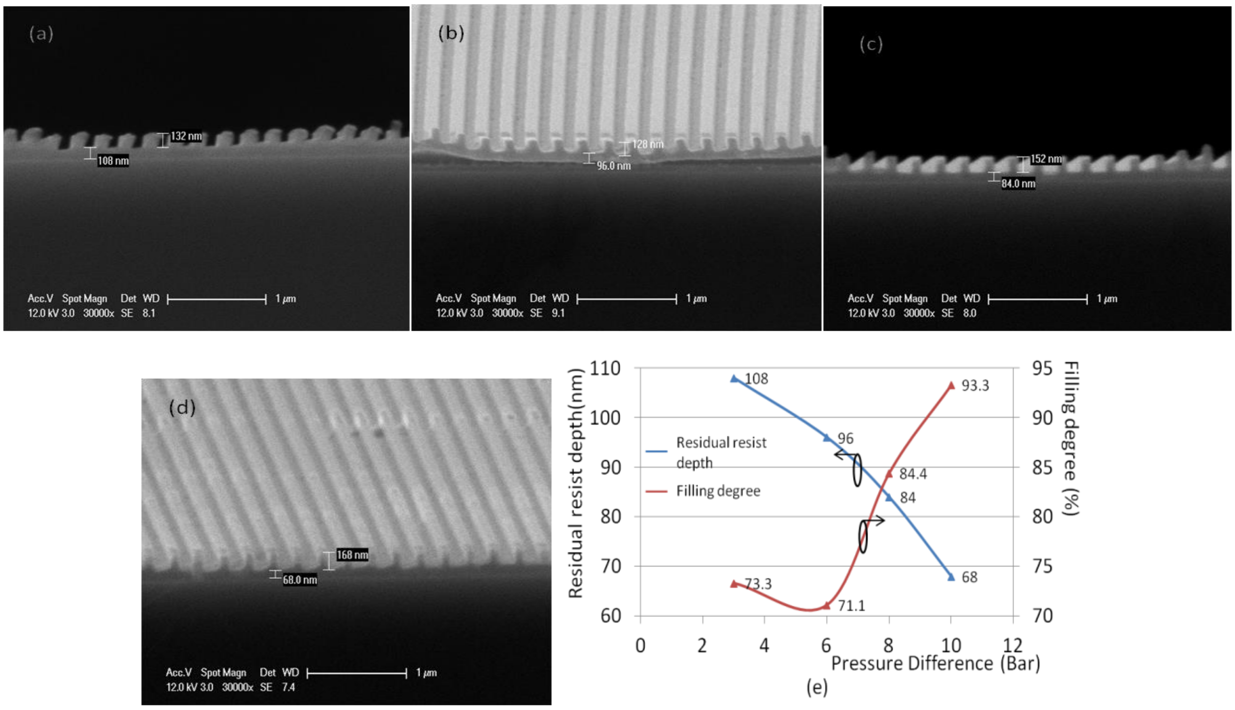

Fig. 5. Grating feature imprinted with the same pressure and the different pressure difference (a) P=15Bar, PD=3Bar (b) P=15Bar, PD=6Bar (c) P=15Bar, PD=8Bar (d) P=15Bar, PD=10Bar (e) grating/residual resist depth variation with the PD at the same pressure

To confirm the performance of the improved method above, the imprint process with the same pressure and different PD has been carried out. As shown in Fig. 5(a), when the P=15Bar and PD=3Bar, the pattern cannot be completely filled. However, with the increasing of the PD, the grating filling degree becomes larger and larger when the residual resist becomes thinner and thinner (Fig.5(e)).

Based on the aforementioned two experimental results, we can see that when both the pressure and PD are low, the pattern cannot be fully filled and consequently a thick residual resist is obtained. However, the use of a relatively high pressure leads to the distortion of the grating. With keeping a low pressure level and increasing the PD, the filling effect becomes better and better with a good shape and a thin residual resist is obtained. In the case of a thin resist, the resist flow is governed by shearing thinning and limited resist supply. Therefore, as to the HPD method, the resist change from the high shear stress to the low one will produce the stress relaxation, which brings the resist flow and deformation [13]. However, the optimized NIL process can effectively solve the contradiction between the filling and distortion.

3.2. Grating etching, removal of etched residual resist, overgrowth and device performance

Following the grating imprinted, the grating etching and resist clean process is coming. The ultraviolet-curable resist will generate cross-link after exposure which is hard to remove by organic solvent. Traditionally, the residual resist is removed by the oxygen plasma bombardment for a long time. However, it sometimes cannot be completely removed, especially for the UV nanoimprint resist. Fig.6(a)-(b) display the grating deals with dry clean but some etched residual resist still exists in the surface. And this resist will degrade the quality of grating burying in the following step. Fig.7 shows the detailed etched grating with wet cleaning and grating with clean surface.

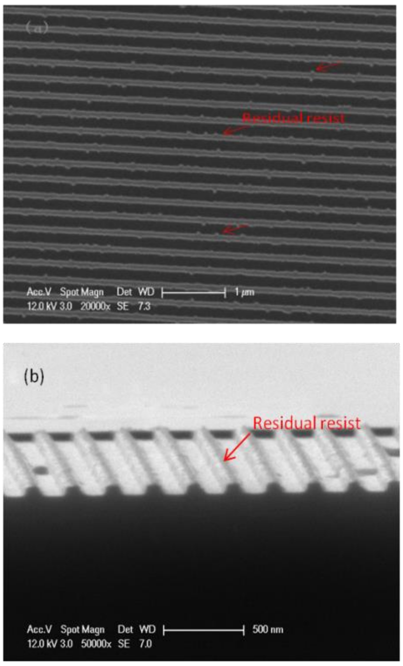

Fig. 6. SEM image of dry cleaning grating (a) surface (b) cross-section

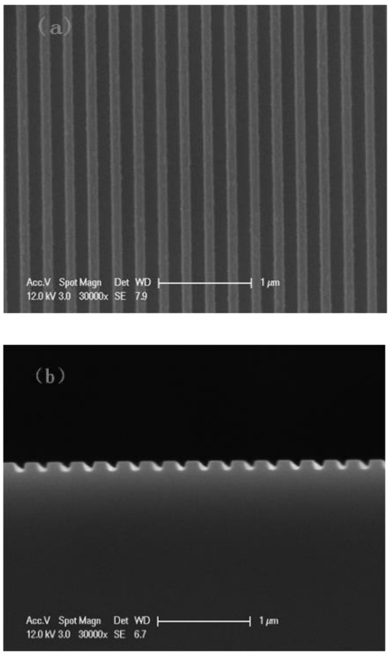

Fig. 7. SEM image of grating with wet cleaning (a) surface (b) cross-section

A comparison of the experimental results mentioned above, we conclude that multi-layer mask method can effectively remove residual resist. Meanwhile, the multi-layer mask method can remove residual resist by employing the HF solution corrosion which does not introduce any additional physical trauma.

After the removal of residual resist, the grating overgrowth process is followed by metal-organic chemical vapor deposition. In the process of the grating overgrowth, unclean surface of the grating will introduce additional lattice defects [14]. Fig. 8(a)-(b) display the buried grating using dry clean and wet clean removal residual resist, respectively. In Fig. 8(a), there are some lattice defects as it is indicated by red arrow. Otherwise, a high quality overgrowth grating is obtained through the wet cleaning post-process method, as Fig. 8(b) shown.

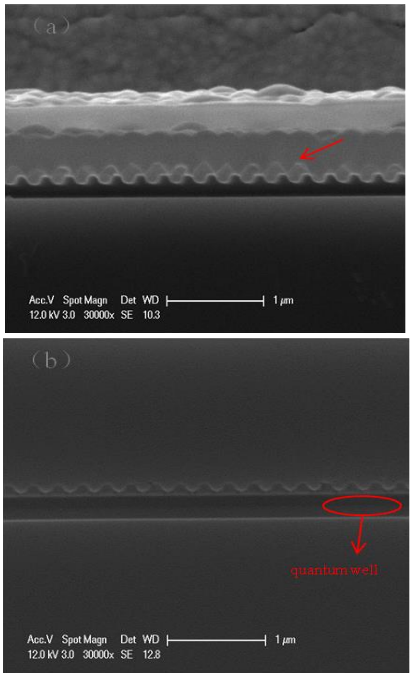

Fig. 8. (a) Buried grating disposal with dry cleaning (b) Buried grating disposal with wet cleaning

Although the grating is a passive structure, the imperfection of the grating directly affects the performance of the laser device. Laser devices with high performance require a high quality overgrowth grating and waveguide layer. Poor quality grating overgrowth possibly generates many lattice defects, which will become strong light scattering centers during the laser operation and consequently increase the internal loss.

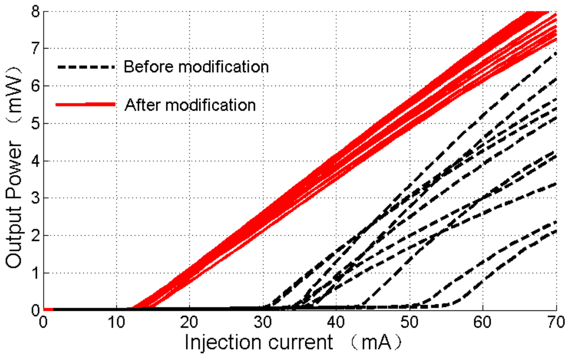

Fig. 9. A typical P-I curves of DFB LD devices at room temperature

We fabricated two batches of DFB laser with different methods to remove the residual resist. As shown by the dashed lines of Fig.9, the threshold current is about 30~55mA, when the grating deals with dry cleaning post-process method while red solid lines show that the threshold characteristics of lasers has been improved obviously, which is smaller than 15mA for all these tested lasers. Moreover, better uniformity is obtained for these lasers with high quality buried grating. As described above, lattice defects become strong light scattering centers during lasing operation and increase the internal loss, therefore the threshold current becomes large.

4. Conclusions

In summary, the HPD NIL procedure is proposed in this paper. With the application of such novel process, the grating with perfect filling is obtained and the grating profile distort is avoided in a low pressure uv-NIL process. In the meantime, the multi-layer mask is fully made use to remove the residual resist and improve the grating burying quality. Experimental results show that grating with clean surface can reduce the lattice defects of overgrowth grating and waveguide layer. Moreover, effects of the overgrowth quality for the laser performance were discussed. The finding indicates that high quality buried grating can enhance the threshold characteristics and uniformity for laser devices. Our experimental results also highlight that the method we proposed can fabricate the diffraction gratings for distributed feedback laser diodes effectively.

Acknowledgements

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