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RESEARCH ARTICLE

DFB LD manufactured by nanoimprint lithography

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Abstract Gratings of distributed feedback laser diodes (DFB LDs) have been successfully manufactured by nanoimprint lithography (NIL). Uniform gratings with periods of about 240 nm and phase-shifted in the center have been fabricated by a soft press NIL employing a polymer stamp technology. Moreover, the shape of the grating is rectangle, rather than sinusoidal by holography. The test results show good characteristics of the electrical and spectral output. The results of this study indicate that NIL has high potential for the manufacture of DFB LDs.

Keywords nanoimprint lithography (NIL), distributed feedback laser diode (DFB LD), soft press, polymer stamp

1 Introduction

Distributed feedback laser diodes (DFB LDs) have the advantages of single-mode operation and stability of wavelength; thus, they are widely used as optical sources in networks. Optical communication networks development is driven by all kinds of Internet applications, such as data, voice, and video transmissions. Therefore, not only does long-haul and high-speed network nodes require good performance but also does metro and access networks require single-mode operation for high speed transmission. Thus, low-cost DFB LDs are increasingly necessary.

DFB LDs with uniform-period gratings suffer double mode problem. An effective way to enhance single-mode property is phase-shifted gratings [1]. Some applications, for example, multi-wavelength DFB LD arrays, require multi-wavelength laser diode (LD) chips on a single wafer. There are various methods for fabricating diffraction gratings, for example, interference exposure, electron beam lithography (EBL), and extreme ultraviolet lithography (EUVL). Interference exposure can only be used for fabricating a uniform period structure, but it cannot feasibly be used for fabricating phase-shifted gratings and multi-wavelength chips. Although EBL has sufficient resolution for phase-shifted gratings, EBL system is expensive and suffers low throughput due to its long writing time across large area. The EUVL with 100 nm resolution is also very expensive, and the multilayer nanoscale alignment function is not needed for the DFB LD manufacturing.

Nanoimprint lithography (NIL) [2,3] is a simple pattern transfer process based on mechanical embossing that is neither limited by diffraction nor scattering effects nor secondary electrons and does not require any sophisticated radiation chemistry either. It is a promising technology for single layer nanopattern duplication due to its low cost and high resolution.

Our research work of using NIL for the fabrication of distributed feedback (DFB) gratings comes from the project of the National Natural Science Foundation of China. In this paper, we have fabricated DFB LD chips, with $\lambda/4$ phase shift in the center, over a 2-inch InP wafer field with good uniformity and output characteristics, and these results show a potential way for DFB LDs mass production.

2 Experimental details

In the manufacturing procedure of a commercial DFB LD, the Bragg grating is fabricated on the upper cladding layer. However, because of the strain or gas distribution during the epitaxial process, the flatness of the epitaxial layer cannot be controlled well, and the nonflatness may reach as high as several hundreds nanometers. If traditional NIL with a hard stamp is applied on this substrate, there will be a few problems. 1) The hard stamp will come in contact with the substrate and may cause damage to the epitaxial

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structure. 2) The high nonflatness of the substrate will cause large “hollow areas” between the substrate and mould and result in large incomplete filling defect areas [3,4]. In this work, a flexible polymer stamp is employed to improve the imprint process. We have used polymer stamp to protect the substrate, prolong the lifetime of stamp, and improve the uniformity of imprinted patterns [5,6].

Before the NIL process, an epitaxial structure consisting of epitaxial layers, such as a buffer layer, waveguide layers, an active layer, and so on, was grown on an InP substrate by metalorganic chemical vapor deposition (MOCVD). Figure 1 shows the process flow of grating fabrication, which is performed with the Etire3 machine from Obducat AB.

First shown in Fig. 1(a), a polymer stamp is fabricated by pressing a hard master stamp against the polymer film through a conversational thermal NIL at 150°C with pressure of 20 Bar. Then, as shown in Fig. 1(b), the polymer stamp is used to transfer patterns onto the final epitaxial structure by simultaneous thermal and ultraviolet (UV) imprint process. In Fig. 1(b), a UV-curable resist (TU2) of 120 nm thickness is spin coated on the substrate first, and then, the temperature is heated up to 60°C to make the resist reach a liquid state. Next, the polymer stamp is pressed into the resist under 40 Bar until the liquid resist has filled all the concaves between the resist and substrate, and a 20 s UV exposure is applied to cure the resist. Then, the stamp is pulled off in one sweep, which is in the direction of the grating [7]. Then, the resin layers are removed by O_2 of 60 SCM under 100 W plasma etching for 15 s. After that, we use inductively coupled plasma reactive ion etching (ICP-RIE) with $CH_4/H_2 = 1:4$ gas under 100 W for 40 s to etch the substrate [8,9]. Finally, the resist masks are removed by O_2 plasma.

After the fabrication of phase-shifted Bragg grating, structures such as a contact layer are formed on the grating layer by MOCVD. Then, the ridge waveguide is formed by chemical etching. Subsequently, a SiO_2 film is deposited as a passivation layer by plasma enhanced chemical vapor deposition (PECVD), and contact holes are formed by selective RIE etching. Finally, metal electrode structure Ti/Pt/Au is formed by high-vacuum evaporation and the lift-off process.

3 Result and discussion

The inspection of imprint results was done by atomic force microscopy (AFM) (Veeco NanoScope MultiMode), scan electron microscope (SEM) (Quanta 200), Olympus BX51 optical microscope.

Figure 2 shows the nanoimprint result of $\lambda/4$ phase-shifted Bragg grating. In Fig. 2, we can see that the grating is straight and with a large area high uniformity. Moreover, the shape of the grating is rectangle, rather than sinusoidal (Fig. 2(c)) by holography [10], and it is more similar to theoretical model used in simulation [11]. The results show that the linewidth of replicated pattern is nearly the same as the silicon master, which proves that NIL can transfer patterns precisely.

The electrical and spectral output properties of the fabricated $\lambda/4$ phase-shifted DFB LDs were measured by LD measurement equipment and Yokogawa AQ6370 optical spectrum analyzer. The threshold current and slope efficiency at room temperature were 11 mA and 0.28 W/A, respectively. Figure 3 shows the output spectrums of the fabricated $\lambda/4$ phase-shifted DFB LD chips. The wavelength of our DFB LD researched is 1566 nm. The

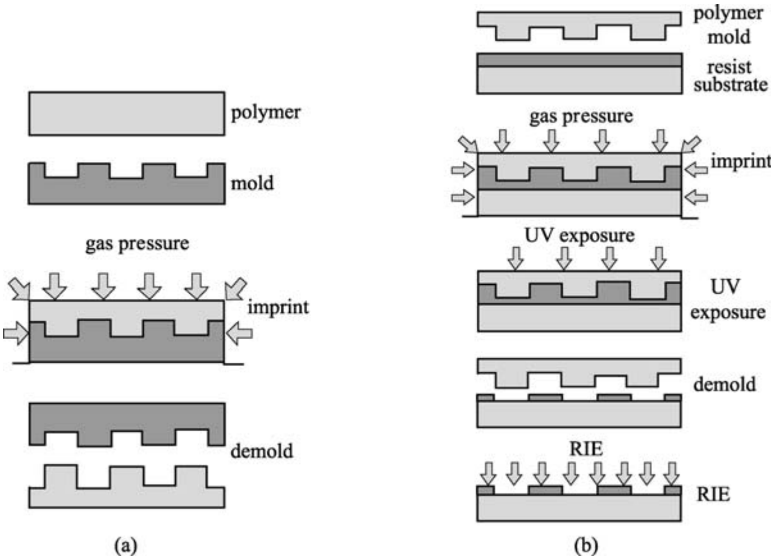


Fig. 1 Schematic diagram process flow of nanoimprint. (a) Fabrication of a polymer stamp; (b) NIL on target substrate using polymer stamp and UV NIL process

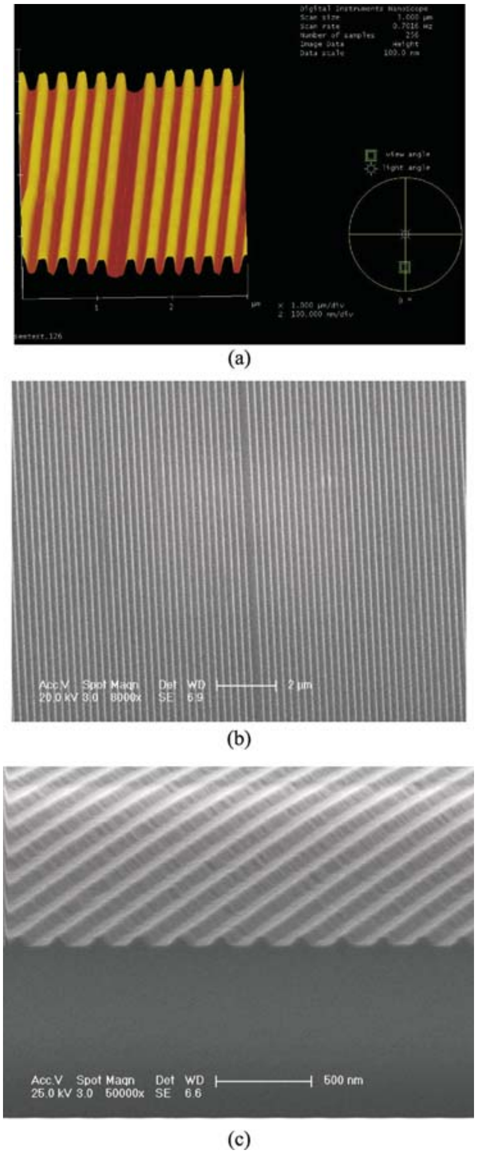
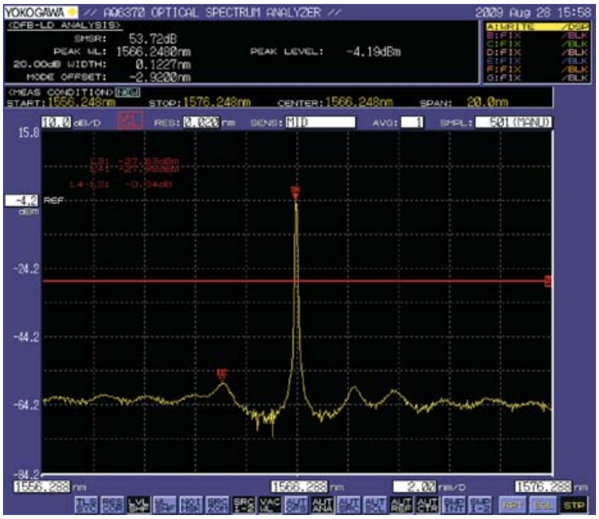


Fig. 2 Grating manufactured by NIL. (a) AFM; (b) SEM; (c) SEM of gratings by holography

side-mode suppression ratio (SMSR) of the DFB LD is measured to be above 50 dB, and the 20 dB width is about 0.12 nm; this demonstrates that the single-mode operation is enhanced by employing $\lambda/4$ phase-shifted gratings.

4 Conclusion

DFB LD chips with $\lambda/4$ phase shift were fabricated on 2-inch wafer with good uniformity employing NIL. The test results show good characteristics of the electrical and spectral output. NIL can provide a few benefits for the DFB LD industry development from its low cost, high resolution, and throughput compared with EBL and EUV.



<DFB-LD ANALYSIS>
SMSR: 53.72dB
PEAK WL: 1566.2480nm
PEAK LEVEL: -4.19dBm
20.00dB WIDTH: 0.1227nm
MODE OFFSET: -2.9200nm

<MEAS CONDITION>
START: 1556.248nm STOP: 1576.248nm CENTER: 1566.248nm SPAN: 20.0nm
10.0 dB/D RES: 0.020 nm SENS: MID AVG: 1 SMPL: 501 (MANU)

Fig. 3 Spectrum of manufactured DFB LD

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