Application of Nanoimprint Lithography to Fabrication of Laser Diodes for Optical Communication Network

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The authors have succeeded in employing nanoimprint lithography (NIL) to form diffraction gratings of distributed feedback laser diodes (DFB LDs), which are increasingly used in optical communication. Uniform gratings and phase-shifted gratings with a period of 232 nm were formed by reversal NIL in combination with the use of a step-and-repeat imprint tool. Line edge roughness has been kept sufficiently low with the fabricated gratings. DFB LDs fabricated by NIL have indicated characteristics comparable to those of LDs fabricated by electron beam lithography, and have also shown high long-term stability in the threshold current.
The authors have also demonstrated that phase-shifted DFB LDs show better uniformity in characteristics than uniform-grating LDs. The results of this study indicate that NIL has high potential for fabricating DFB LDs.

Keywords: nanoimprint, distributed feedback laser, optical communication, diffraction grating

1. Introduction

1-1 Market status of laser diodes for optical communication

The recent growth of the Internet, mobile telecommunication, video on demand services, and other information-communication facilities has led to the explosion of worldwide communication traffic, leading to demand for faster and denser communication infrastructures including optical communication networks. Distributed feedback laser diodes (DFB LDs) have been widely used as optical sources in networks because of their high selectivity and stability of wavelength. Though they have mainly been used in long-haul and high-speed networks, they are now increasingly required in metro and end-user fields because of the increasing traffic. Thus, necessity for inexpensive DFB LDs increases rapidly.

Sumitomo Electric supplies DFB LDs to the optical communication market as one of the strategic products in optical device business. Innovations in fabrication techniques featuring low cost have been indispensable to meet the demand for inexpensive DFB LDs.

1-2 Nanoimprint lithography

Nanoimprint lithography (NIL) is a patterning technique, transferring relief patterns formed on a master mold to resin on a substrate, applicable to forming fine figures with the size of sub-micrometer or smaller. In 1995, Chou et al. indicated that sub-10-nm features could be formed by imprinting, which triggered the start of NIL technology(1). The new technology is promising as a manufacturing process of micro- and nanodevices because of its high resolution comparable to that of electron beam lithography (EBL) and its much higher throughput than that of EBL. Low initial and running cost is also advantageous to research in various application fields. Various process methods and apparatuses suitable for each application field, for example, next generation storage media(2), optical devices such as wavelength filters(3), and nanofluidics(4), are suggested and studied in the world.

2. Motivation

DFB LDs have the advantages of homogeneity and stability in emission wavelength, which depends on the period of diffraction gratings formed adjacent to the active layer (**Fig. 1**)(5). However, we have had difficulty in reducing the fabrication cost of DFB LDs, because exceedingly high order of accuracy is required for forming the diffraction gratings with the linewidth from 100 nm to 130 nm. Moreover, it is a crucial issue that the basic characteristics of DFB LDs, such as the threshold current and the output power, depend on the grating phase at the cleaved facet(6), because it leads to reduction in production yields. One of the most effective ways of reducing the dependence on the facet phase is to convert uniform gratings into phase-shifted gratings (**Fig. 2**)(7). In general, there are various methods for fabricating diffraction gratings, for example, interference exposure, electron beam lithography (EBL), and optical projection exposure. Interference exposure cannot feasibly be used for fabricating phase-shifted gratings, because it exclusively generates exposure patterns with a uniform bright-and-dark period. Although EBL has sufficient resolution to be used for phase-shifted gratings, exceedingly

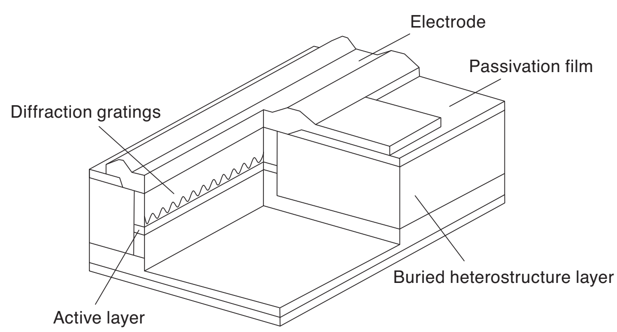

Fig. 1. Schematic structure of a DFB LD.

expensive EBL systems are necessary for mass production with sufficient throughput. For the optical projection method, a forefront stepper having sufficient resolution is also expensive, and the cost is too high for fabricating DFB LDs, of which production volume is relatively small compared to that of such semiconductor devices as large scale integrations (LSIs).

We started investigating the use of NIL for fabricating diffraction gratings several years ago, because we have considered the new technology as a possible solution to the above issues because of its high resolution, throughput, and low cost[(8),(9)].

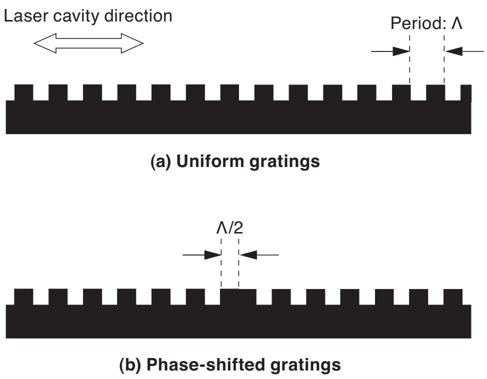

Fig. 2. Schematic structures of uniform gratings (a) and phase-shifted gratings (b).

3. Experimental Procedure

Using NIL as a fabrication method of phase-shifted DFB LDs, we have paid attention to the two issues. One of the issues is mechanical damage in epitaxial layers induced by imprinting pressure, because compound semiconductor crystals used for LDs are easily damaged by mechanical stress. Crystal defects increased by mechanical stress lead to serious deterioration in the characteristics and reliability of the semiconductor devices[(10)]. Another issue is nonuniformity in the thickness of residual resin after the imprinting because of the geographical variation of the substrate surface. Commercially available compound semiconductor substrates, such as GaAs, InP, and GaN, have large undulations compared with Si substrates. Applying NIL to such undulating substrates, it is possible that the mold will come in contact with a limited portion of the substrate, in which case severe nonuniformity of the residual layer thickness in the imprinted area will lead to large variations of the figures in the transferred patterns.

It is difficult to solve these issues simultaneously because the increase of imprinting pressure for higher uniformity leads to higher damage in semiconductor substrates. Thus, we have clarified the damage in semiconductor crystal by using a non-contact evaluation method. In order to improve the uniformity, we have not only adopted a reversal NIL process but also advanced the resin etching after imprinting. Moreover, we have fabricated phase-shifted DFB LDs by utilizing NIL in order to evaluate the characteristics and long-term reliability.

4. Fabrication Process

In this study, diffraction gratings are formed onto the active layer (**Fig. 1**), which is buried with a semi-insulating InP layer doped with Fe. The fabrication procedure of diffraction gratings is shown in **Fig. 3**. First, a primer material is spin-coated on a substrate, on which the epitaxial layers including an active layer have been formed. Next, UV-curable resin is dispensed on the primer layer, then a quartz glass mold with grating patterns is pressed on the UV-curable resin (**Fig. 3 (a)**). We have used the mold containing diffraction gratings with the period of 232.4 nm, which cor-

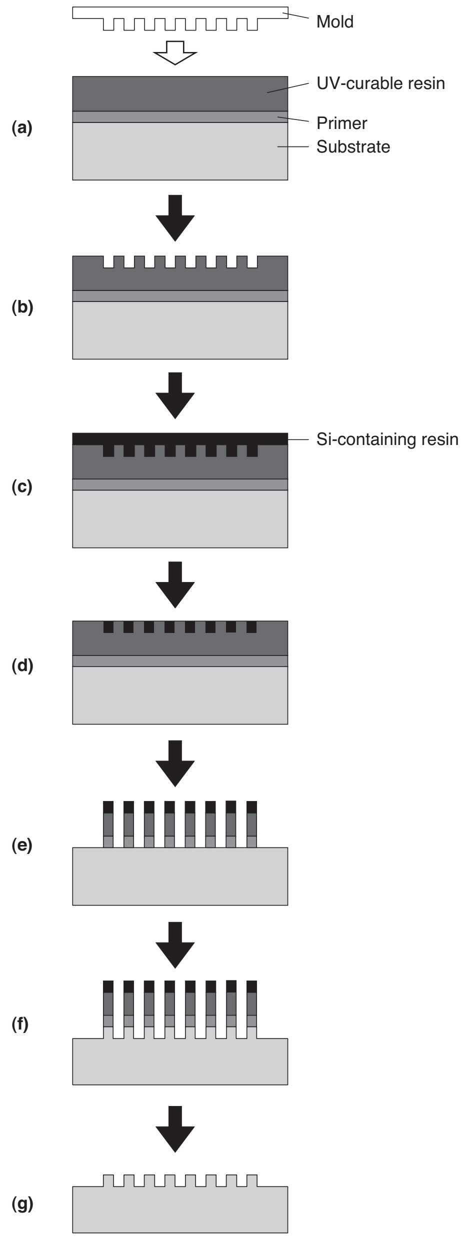

Fig. 3. Fabrication process of diffraction gratings.

responds to the emission wavelength of LDs with 1490 nm. Although imprinting pressure is relatively small, less than 0.1 MPa; UV-curable resin spreads widely in the lateral direction and sufficiently fills the groove in the mold, because the resin has relatively low viscosity. Subsequently, UV light is irradiated through the mold to harden the resin, and then the mold is released from the substrate (**Fig. 3 (b)**). After a cycle of the imprinting described above is finished, the sample stage moves to the next field and the cycle is repeated (step and repeat). The filed size was approximately 9 mm × 7 mm. After that, Si-containing resin is spin-coated to cover the grating corrugations (**Fig. 3 (c)**). The thickness of the resin is approximately 240 nm. Subsequently, the Si-containing layer is etched by inductively coupled plasma reactive ion etching (ICP-RIE) until the tops of the corrugations are revealed (**Fig. 3 (d)**). We have used CF_4 and O_2 gases for this etching. After that, the revealed layer is selectively etched by the ICP-RIE system with O_2 and N_2 gases until the substrate is revealed (**Fig. 3 (e)**), then the resulted resin patterns are used as masks for the subsequent etching, which transfers the grating patterns to the substrate (**Fig. 3 (f)**). We have used the ICP-RIE system with CH_4 and H_2 gases for the substrate etching. Finally, the resin layers are removed by O_2 plasma etching (**Fig. 3 (g)**).

As described above, by adopting the reversal NIL process, we have suppressed the nonuniformity of pattern figures caused by the geographical variation of the substrate to a certain extent. The fabrication process of DFB LDs that we employ in this study is based on our standard and mature process except for the fabrication steps of diffraction gratings.

5. Influence of Imprinting Pressure

In order to evaluate the mechanical damage in semiconductor crystal induced by imprinting pressure, we have investigated deterioration of photoluminescence (PL) intensities from the epitaxial layers. We prepared two indium-phosphide substrates with epitaxial layers and a blank (with no patterns) mold. We have compared PL intensities between the two samples: imprinted with UV-curable resin between the mold and the substrate, and imprinted without resin. The size of the mold was 10 mm x 10 mm, and the imprinting pressure was approximately 0.8 MPa for both samples. The resin on the former sample was removed before PL measurement.

The results are shown in **Fig. 4**. The sample without resin shows evident deterioration of PL intensities. On the other hand, no evident deterioration is found in the sample with resin. These results indicate that the resin functions as a cushion to prevent severe damage by imprinting pressure.

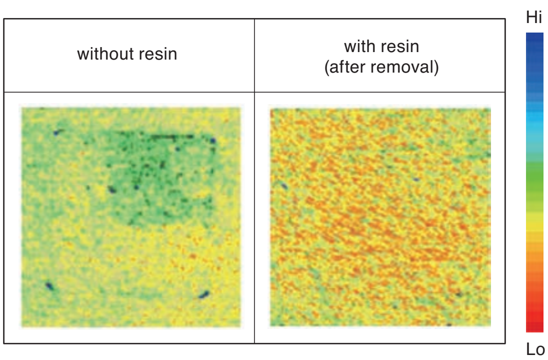

Fig. 4. Comparison of photoluminescence intensities between two samples: imprinted without resin (left) and imprinted with resin (right). The field size of imprinting is 10 mm × 10 mm.

6. Improvement of Uniformity

As described above, thickness variation of residual resin caused by the undulation of substrates is one of the serious issues for application of the NIL to the LD fabrication. Although we have improved the uniformity by employing the reversal NIL method, the effect is not sufficient for satisfying the requirement from the viewpoint of production. We have considered that suppressing undercut during the penetration etching (**Fig. 3 (e)**) is effective in the improvement of the uniformity even if the thickness variation is not negligible. Thus, we have investigated the etching conditions, and finally we have found the optimal condition using N_2 for the process gas. Under this etching condition, reaction products containing nitrogen atoms are deposited on the etched surface, and the lateral etching of the sidewalls of grating protrusions is suppressed. Moreover, we have employed a cooling system of the substrate in order to increase the effect of the sidewall protection. In conclusion, we have obtained exceedingly high uniformity in the linewidth of gratings. The variation of the linewidth across a 2-in. substrate, in which the thickness variation of residual resin was approximately 300 nm, was less than 10 nm in 3σ. A cross-sectional view of the sample after resin etching is shown in **Fig. 5**.

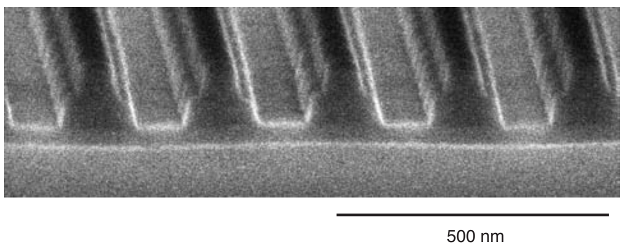

Fig. 5. Cross-sectional SEM image of gratings after the penetration etching of the resin.

7. Characteristics of LDs

Figure 6 shows a scanning electron microscope (SEM) image of the fabricated diffraction gratings after the removal of the resin following the crystal etching (**Fig. 3 (g)**). It demonstrates that the line edge roughness of the gratings is markedly low, indicating that the master patterns are precisely transferred to the substrate by the imprinting and the subsequent etching process. We have evaluated the period of the fabricated gratings by measuring the diffraction angle of incident light with the wavelength of 364 nm, and 232.4 nm ± 0.1 nm is obtained in the period just as we targeted.

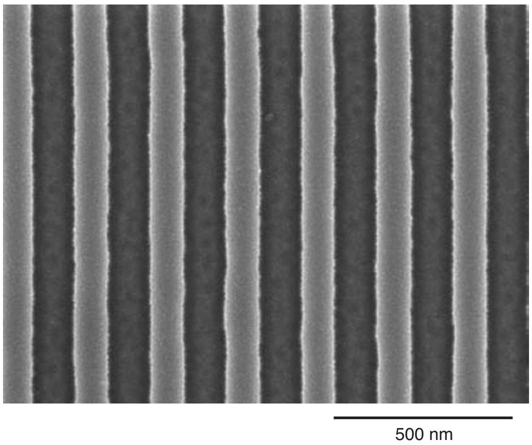

Fig. 6. SEM image of diffraction gratings after the crystal etching.

Figure 7 shows the dependence of the optical output power and the slope efficiency on the supplied current for a typical phase-shifted DFB LD fabricated in this study. The threshold current at room temperature was measured to be 8 mA, which are comparable to those of typical uniform-grating DFB LDs fabricated simultaneously on the same substrate.

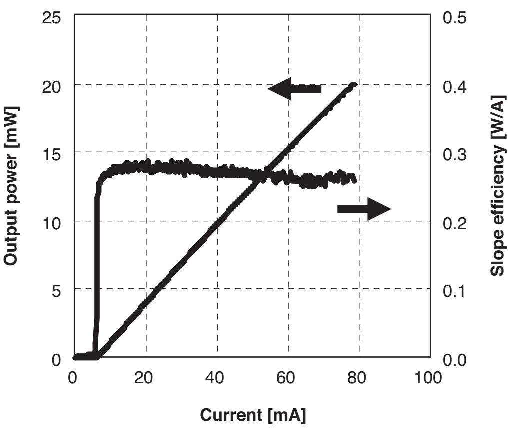

Fig. 7. Supplied current vs. optical output and slope efficiency.

Figure 8 shows the oscillation spectrum of a phase-shifted DFB LD. It demonstrates that the peak wavelength corresponds to the Bragg wavelength at the center of the stopband, indicating that the phase-shifted gratings function properly.

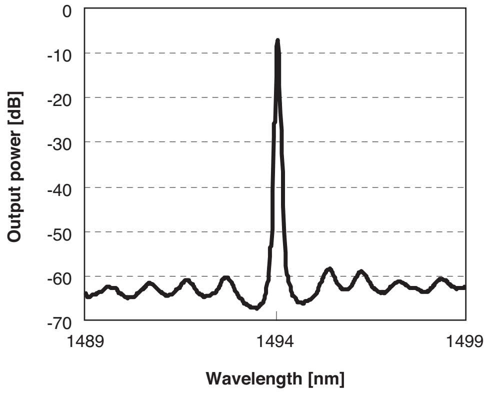

Fig. 8. Oscillation spectrum of a phase-shifted LD.

We have compared the side-mode suppression ratio (SMSR) of phase-shifted LDs fabricated by NIL with those fabricated by EBL. SMSR is one of the parameters indicating the stability of the single-mode emission of DFB LDs. Histograms of SMSR for the both types of LD are shown in **Fig. 9**, which demonstrate that they show comparable variations in SMSR.

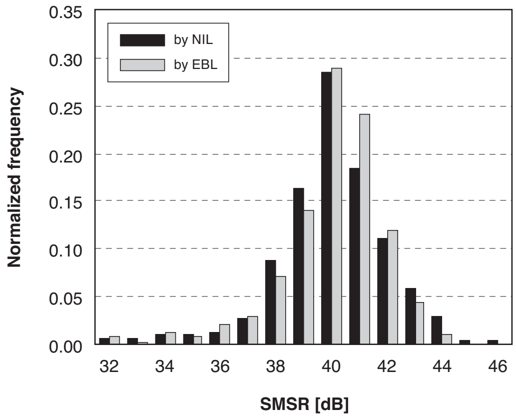

Fig. 9. Histograms of SMSR for phase-shifted LDs fabricated by NIL and by EBL. The standard deviations of SMSR for LDs fabricated by NIL and by EBL are almost the same, 2.0 and 1.8, respectively.

We have also compared the maximum output power of the phase-shifted LDs with those of the uniform grating LDs. The both types of LD are simultaneously fabricated on the same substrate by using NIL. As shown in **Fig. 10**, the variation of the output power of the phase-shifted LDs is evidently smaller than those of uniform-grating ones. The standard deviation of the output power for the phase-shifted LDs is 0.74 mW, which is 40% smaller than that for the uniform-grating ones, 1.27 mW. This demonstrates that the both types of diffraction gratings have been successfully formed as we designed by the new fabrication process utilizing NIL.

We have investigated long-term reliability of fabricated DFB LDs. **Figure 11** shows the time-dependent change in the threshold current of the phase-shifted LDs with the output power of 10 mW at the ambient temperature of 85˚C. The change in the threshold current after 5000 hours is less than ±1%, demonstrating that the phase-shifted LDs fabricated in this study have high stability. This result indicates that imprinting pressure causes no serious damage to the quality of LDs.

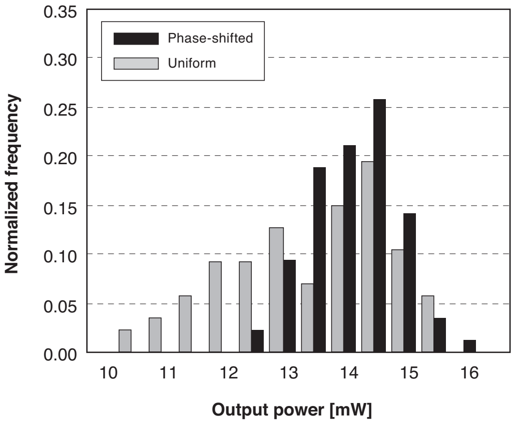

Fig. 10. Histograms of maximum output power for phase-shifted LDs and uniform-grating LDs fabricated by NIL. The standard deviations of output power for phase-shifted LDs and uniform-grating LDs are 0.74 and 1.27, respectively.

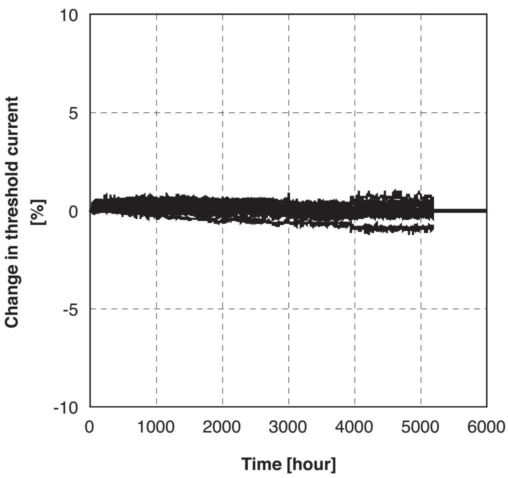

Fig. 11. Time-dependent change in threshold current of phase-shifted DFB LDs with the output power of 10 mW at the ambient temperature of 85°C.

8. Conclusions

NIL process has been employed for fabricating the diffraction gratings of DFB LDs used for the optical communication. We have adopted the reversal NIL method, and optimized the process of the resin etching in order to suppress the nonuniformity of pattern figures. Less than 10 nm in 3σ is obtained in the variation of the linewidth across a 2-in. substrate.

We have successfully demonstrated the fabrication of diffraction gratings of DFB LDs by NIL, which have comparable characteristics to those fabricated by EBL. We have also verified the feasibility of fabricating phase-shifted LDs by demonstrating that the uniformity of the output power is improved by 40% compared with that of uniform-grating LDs. Moreover, we have shown that the change in the threshold current after 5000-hour reliability test is less than ±1%, demonstrating that the phase-shifted LDs fabricated in this study have exceedingly high stability.

As described above, NIL is an effective and promising process for fabricating phase-shifted DFB LDs and is expected to have the advantage of mass-production capability in the near future from the view point of high throughput and low cost. We conclude that NIL has high potential for fabricating DFB LDs, and we also expect that NIL will be used for fabricating various optical devices consisting of nanostructures.

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