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To cite this article: M Yanagisawa et al 2009 J. Phys.: Conf. Ser. 191 012007

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Evaluation of nanoimprint lithography as a fabrication method of distributed feedback laser diodes

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Abstract. We have succeeded in employing nanoimprint lithography (NIL) to form the diffraction gratings of distributed feedback laser diodes (DFB LDs) used in optical communication. Uniform gratings and phase-shifted gratings with periods of 232 nm have been formed by using a reverse NIL with a step-and-repeat imprint tool. Line edge roughness has been sufficiently low with the fabricated gratings. DFB LDs fabricated by NIL have indicated comparable characteristics with LDs fabricated by electron beam lithography. We have also demonstrated that phase-shifted DFB LDs show better uniformity in characteristics than uniform-grating DFB LDs. The results of this study indicate that NIL has high potential for the fabrication of DFB LDs.

1. Introduction
Worldwide communication traffic has risen rapidly because of the growth of the Internet, mobile telecommunication, video-on-demand services, and other information-communication facilities. This growth has led to demand for faster and denser communication infrastructures including optical communication networks. Distributed feedback laser diodes (DFB LDs) have the advantages of high selectivity and stability of wavelength; thus, they are widely used as optical sources in networks. They have mainly been used in long-haul and high-speed network nodes, but they are now increasingly required in metro and end-user fields because of increasing traffic. Thus, inexpensive DFB LDs are becoming increasingly necessary.

DFB LDs with uniform-period gratings have been widely used for optical networks. The characteristics of a DFB LD with uniform gratings depend on the grating phase at the cleaved facet [1]. This variation of characteristics with the facet phase is a serious issue from the viewpoints of productivity and usability. One of the most effective ways of reducing the dependence on the facet phase is to convert uniform gratings into phase-shifted gratings [2]. 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,

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exceedingly 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 LSIs.

Nanoimprint lithography (NIL) has been studied by many organizations since the middle of the 1990s. Chou et al. showed that sub-10-nm features could be formed by imprinting, which triggered the start of NIL technology [3]. A novel method of NIL using a UV-curable polymer was introduced by Haisma et al [4]. Bailey et al. demonstrated a method of step-and-repeat imprinting named SFIL [5].

We started investigating the use of NIL for fabricating diffraction gratings several years ago, because we considered the new technology as a possible solution to the above issues because of its high resolution, throughput, and low cost. In this study, we have used NIL to form phase-shifted gratings of DFB LDs, and we have evaluated its potential as a process for fabricating DFB LDs. We have paid attention to the two technical issues in fabricating DFB LDs: uniformity of residual layer thickness, and mechanical damage in the epitaxial layer caused by imprinting pressure. In this report, we demonstrate the evaluation results of the above issues, and the characteristics of fabricated DFB LDs.

2. Experimental Procedure
Commecially available compound semiconductor substrates, such as GaAs, InP, and GaN, have large undulations compared with Si substrates used for LSIs, of which the total thickness variation typically exceeds 5 µm. When 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. Thus, we have formed diffraction gratings on a grating layer by using a reverse imprint based on SFIL/R, developed by Molecular Imprints, in order to suppress the variation of residual layer thickness resulting from the undulation of substrates [6]. We have aimed to improve the uniformity of the figures of grating corrugations by using the SFIL/R process.

Schematic structures of the LD and its epitaxial layers are shown in figures 1(a) and 1(b), respectively. We have prepared an InP substrate with epitaxial layers including an active layer, a grating layer, and a lower cladding layer grown by metalorganic vapor phase epitaxy (MOVPE). The fabrication procedure is shown in figure 2. First, a 50-nm-thick SiON film is deposited on the substrate by plasma-enhanced chemical vapor deposition. Next, a primer material is spin-coated in order to increase adhesion between UV-curable resin and the SiON film. Then, UV-NIL with a quartz glass mold is conducted to form patterns of diffraction gratings on the primer layer [figures 2(a) and 2(b)]. In this study, imprinting was performed in 16 fields on a substrate with a step-and-repeat

![Figure 1. Schematic structure of the DFB LD (a) and its epitaxial layers (b).](image-url)
equipment. After that, Si-containing resin is spin-coated to cover the grating corrugations [figure 2(c)]. Subsequently, the Si-containing layer is etched by reactive ion etching (RIE) until the tops of the corrugations are revealed [figure 2(d)]. After that, the revealed layer is selectively etched by RIE until the SiON masks are revealed [figure 2(e)], and the formed patterns are used as masks for the subsequent etching, which transfers the grating patterns to the SiON masks [figure 2(f)]. Subsequently, the resin layers are removed by O₂ plasma etching. After that, we use inductively coupled plasma RIE (ICP-RIE) with CH₄/H₂ gas to etch the substrate [figure 2(g)]. Finally, the SiON masks are removed by a wet chemical process using HF solution. After the formation of diffraction gratings, an upper cladding layer and contact layers are formed on the grating layer by MOVPE. The contact layers consist of InP and InGaAs layers [figure 1(b)]. Then, stripe patterns of SiO₂ are formed on the contact layers to define the cavities of the LDs. The stripe patterns are used as masks for subsequent crystal etching by ICP-RIE with CH₄/H₂ gas. After that, Fe-doped InP is selectively grown as an insulating layer by MOVPE. Subsequently, a SiO₂ film is deposited as a passivation layer, in which contact holes are formed by selective etching by RIE. Finally, metal electrodes are formed by high-vacuum evaporation and the lift-off method.

We have formed diffraction gratings with periods from 200 to 260 nm by using molds with corresponding periods. In this study, we used a mold with a period of 232 nm because we aimed to fabricate DFB LDs with a wavelength of 1.49 µm.

As described above, we used the S-FIL/R process so that the variation of the residual thickness has been minimized. However, the effect of the planarization of the S-FIL/R process is not sufficient for fabricating LDs in high yield, and more progress in uniformity of the residual thickness is required. Thus, we have attempted to reduce the field size of the mold.

In order to evaluate the mechanical damage, we have investigated deterioration of photoluminescence (PL) intensities of the epitaxial layers after imprinting.

Figure 2. Fabrication process of the gratings.
3. Results and Discussion

A scanning electron microscope image of the fabricated diffraction gratings is shown in figure 3. It demonstrates that the line edge roughness (LER) of the gratings is markedly low, indicating that the LER of the grating corrugations in the master mold is sufficiently suppressed and that the master patterns are precisely transferred to the substrate by imprinting. The depth of the diffraction gratings was measured to be approximately 20 nm by an atomic force microscope.

Figures 4(a) and 4(b) are bird’s-eye photographs of imprinted substrates. The field sizes in figure 4(a) and figure 4(b) are 14 mm x 18 mm and 7 mm x 9 mm, respectively. They demonstrate that reducing the field size leads to reducing the variation of the residual thickness across the substrate. It is because reducing the field size of a mold corresponds to reducing the variation of the gap between a mold and a substrate within an imprinted field.

We have used a photoluminescence method in order to evaluate the deterioration of crystals. We prepared two indium-phosphide substrates with epitaxial layers. We compared photoluminescence intensities between the two samples: imprinted without resin, and imprinted with resin on it. The results are shown in figure 5. The sample without resin shows evident deterioration of PL intensities. The degradation of intensity is distributed in the edge of the imprinted area. This means that the pressure of imprinting concentrates near the edge of the mold. 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 in epitaxial layers by imprinting pressure.

Figure 6 shows the dependence of the optical output and slope efficiency on the supplied current for a typical phase-shifted DFB LD fabricated in this study. The threshold current and slope efficiency at room temperature were measured to be 8 mA and 0.28 W/A, respectively, which are comparable to those of typical uniform-grating DFB LDs fabricated simultaneously on the same substrate.

Figure 7 shows the oscillation spectrum of a phase-shifted LD. The resolution of the wavelength is 0.02 nm. This demonstrates that the peak wavelength corresponds to the Bragg wavelength at the center of the stopband, indicating that the phase-shifted gratings function properly.

Figure 8. Histograms of SSR for phase-shifted LDs fabricated by NIL and by EBL. The standard deviations of SSR for LDs fabricated by NIL and by EBL are almost the same, 2.0 and 1.8, respectively.

Figure 9. Histograms of SSR for phase-shifted LDs and uniform-grating LDs fabricated by NIL. The standard deviations of SSR for phase-shifted LDs and uniform-grating LDs are 2.0 and 2.5, respectively.
We have compared the side-mode suppression ratio (SSR) of phase-shifted LDs fabricated by NIL with those fabricated by EBL. SSR is one of the parameters indicating the stability of the single-mode emission of DFB LDs. Histograms of SSR for both types of LD are shown in figure 8, which demonstrate that they show comparable variations in SSR.

The histogram of SSR for phase-shifted LDs is compared with that for uniform-grating LDs in figure 9. The two types of LDs were sampled from the same substrate, and the number of samples is 305 for each type of LD. The standard deviation of SSR for the phase-shifted LDs is 2.0, which is smaller than that for the uniform-grating LDs, 2.5. This demonstrates that the stability of the single-mode emission is improved by the effect of phase-shifted gratings.

As described above, we have successfully fabricated phase-shifted DFB LDs by NIL that are comparable to those fabricated by the conventional EBL process, and we have demonstrated that the uniformity of SSR is improved compared with that for uniform-grating LDs.

4. Conclusions
We have successfully demonstrated the fabrication of phase-shifted 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 LD characteristics is improved compared with those of uniform-grating LDs.

NIL is expected to be used as a fabrication process for many applications. However, there are still some difficulties with its use as a mass-production process, for example, defects and low throughput in patterned media, defects and poor alignment accuracy in semiconductor lithography, and the necessary of increasing field size and throughput in displays. Although those difficulties may be common to the fabrication of DFB LDs, they would not be insurmountable problems. Even if defects in the imprinted pattern influence the yield of LDs, inferior chips could be easily rejected because each dye is as small as approximately 300 μm. There is no need for a larger field size than a 3-in.-diameter circle, because compound semiconductor substrates used for LDs are wafers of 3-in. diameter or smaller. Regarding alignment accuracy, an error of up to approximately 5 μm is acceptable. Also, even if throughput is limited to less than one wafer per hour, NIL would still have a higher throughput than EBL.

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. We conclude that NIL has high potential for fabricating DFB LDs, and we expect that NIL will be used for fabricating various optical devices consisting of nanostructures.

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