1.3 µm Wavelength AlGaInAs/InP Ridge-Waveguide Lasers Utilizing Benzocyclobutene Planarization Process

Hideki YAGI*, Yutaka ONISHI, Kenji KOYAMA, Yukihiro TSUJI, Hiroyuki ICHIKAWA,
Hiroyuki YOSHINAGA, Noriaki KAIDA, Toshio NOMAGUCHI, Kenji HIRATSUKA
and Katsumi UESAKA

Aiming at high-speed direct modulation over 10 Gbit/s, we have developed 1.3 µm wavelength AlGaInAs/InP distributed feedback (DFB) lasers with a ridge-waveguide structure planarized by benzocyclobutene (BCB) polymers. The lasers recorded wide electrical bandwidths of more than 20 GHz owing to reduction in parasitic capacitance by the effects of the BCB buried structure. A clear eye-opening was also observed under 26 Gbit/s direct modulation with the extinction ratio of 6 dB at a measurement temperature of 25 °C. Furthermore, 14 Gbit/s uncooled operation up to 85 °C was achieved with the extinction ratio of 5 dB. This report highlights the high potential of ridge-waveguide lasers utilizing the BCB planarization process as a light source for high-speed direct modulation over 10 Gbit/s.

Keywords: AlGaInAs/InP, DFB laser, ridge-waveguide structure, BCB planarization process

1. Introduction

The rapid increase of data communication expedites the standardization of high-speed communication systems, such as 100 Gbit/s ethernet (100 GbE) and 16 Gbit/s Fibre Channel (16GFC). 100GbE system utilizes wavelength division multiplexing (WDM) techniques and uses four cooled lasers, each of which is modulated at 26 Gbit/s as light sources of a transmitter. In the case of 16 GFC, an uncooled operation of a laser at 14 Gbit/s is preferable to meet the restricted power consumption. To realize these lasers, we have studied a directly modulated laser since it affords lower cost and power consumption compared with distributed feedback (DFB) lasers integrated with an electro-absorption (EA) modulator.

In order to realize lasers with high-speed direct modulation of more than 10 Gbit/s, both high modulation efficiency and wide electrical bandwidth are essential. For obtaining the high modulation efficiency, an AlGaInAs multiple-quantum-well (MQW) structure is suitable because it has higher differential gain than a GaInAsP MQW structure due to its larger conduction band offset (1)-(5). A ridge-waveguide (RWG) structure offers wider electrical bandwidth than a buried heterostructure (BH) because it does not have p- and n-type InP current blocking layers, which cause parasitic capacitances, along the side of laser active region. The planarization process using the benzocyclobutene (BCB) polymer, which can be used for a passivation of a mesa structure (6), (7), is also very useful in the reduction of parasitic capacitance between a substrate and an electrode owing to its low relative dielectric constant (2.50 – 2.65).

In this paper, we would like to report 14 Gbit/s and 26 Gbit/s direct modulation of AlGaInAs/InP DFB lasers with the RWG structure planarized by BCB polymers.

2. Fabrication Process

Figure 1 shows the fabrication process of RWG DFB lasers buried by BCB polymers. Firstly, an AlGaInAs compressively-strained MQW structure was grown on an n^+-InP (100) substrate by organometallic vapor-phase-epitaxial (OMVPE) growth. After the formation of uniform DFB grating by electron beam (EB) lithography and dry etching, the regrowth processes of a p-InP cladding layer and a p^+-GaInAs contact layer were done by OMVPE.

RWG structures were fabricated by photolithography and CH_4/H_2-reactive ion etching (RIE) using SiN mask. Then, the deposition of SiO_2 and coating of BCB polymers were carried out on the RWG structure. Here, we used the non-photosensitive BCB polymer because the exposure process of the photosensitive BCB during photolithography causes the instability of the BCB opening shape, resulting in the deterioration of a yield. BCB opening patterns on the top of the stripe were formed by photolithography and CF_4/O_2-RIE. SiO_2 window patterns were fabricated on the contact layer with the self-aligned process using CF_4-RIE without resist patterning.

Next, electrodes were evaporated on p- and n-side surfaces. **Photo 1** shows the cross-sectional scanning electron microscope (SEM) image of the RWG structure after the electrode evaporation. The good shape of the BCB/SiO_2 opening pattern without any disconnection of the electrode could be obtained by using this simple process. The thickness of the BCB polymer under the electrode-pad was also approximately 1 µm.

Finally, anti-reflection (AR) and high-reflection (HR) coatings were applied on the front facet and the rear facet, respectively.

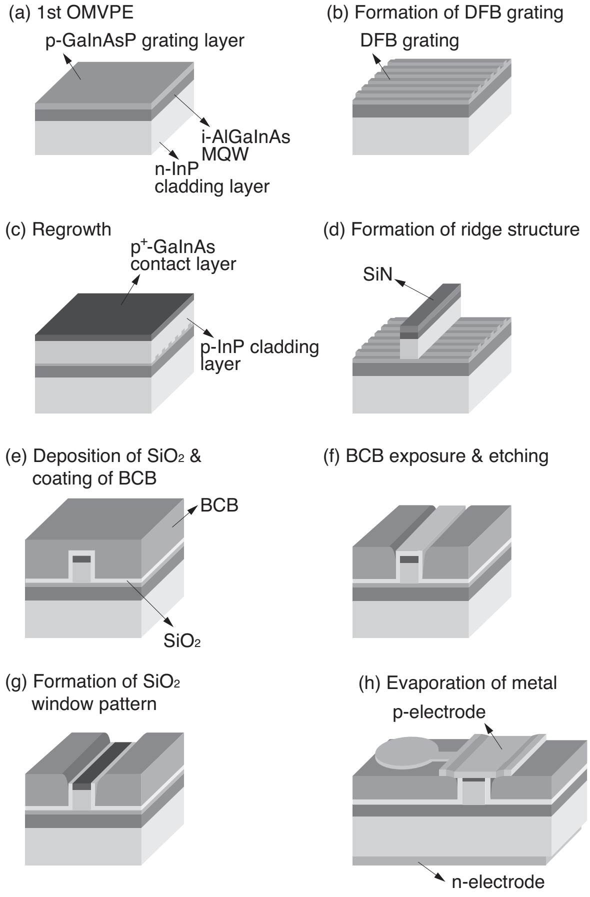

Fig. 1. Fabrication process of the RWG DFB laser buried by BCB polymers

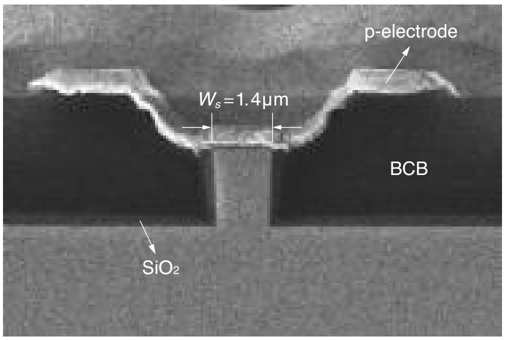

Photo 1. Cross-sectional SEM image of the RWG structure after the electrode evaporation

3. Laser Characteristics

Figure 2 shows the electrical response of the fabricated RWG laser, which was extracted from the electro-optic response. In this RWG structure, 3-dB down frequency bandwidth of more than 20 GHz was acquired. This wide electrical bandwidth is attributed to the reduction of parasitic capacitance by burying the mesa structure using BCB polymers.

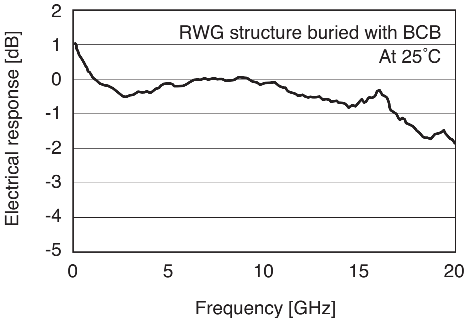

Fig. 2. Electrical response for the RWG structure buried with BCB polymers

Figure 3 shows light output characteristics of the fabricated RWG DFB laser under the continuous wave (CW) operation. The cavity length (L) and the stripe width (W_s) of this laser were 250 μm and 1.1 μm. The threshold current and the slope efficiency at 25 °C were 13 mA and 0.41 W/A, respectively. These at 85 °C were 31 mA and 0.25 W/A, respectively. The device resistance was estimated to be around 6 Ω. We also confirmed the sub-mode suppression ratio (SMSR) of more than 35 dB in the temperature range from 25 °C to 85 °C.

Next, we measured the relaxation oscillation frequency (f_r). **Figure 4** shows the square root of the bias current dependence of f_r for RWG DFB lasers at measurement temperatures of 25 °C and 85 °C. The DFB grating has the detuning (Δλ =Bragg wavelength (λ_B) − Gain peak wavelength (λ_G)) of −1.7 nm and −6.7 nm. As can be seen, the slope value at 25 °C was estimated to be 2.7 GHz/mA$^{1/2}$ and 3.1 GHz/mA$^{1/2}$ for the detuning of −1.7 nm and −6.7 nm, respectively. At 85 °C, the slope values were 2.3 GHz/mA$^{1/2}$ for both detuning cases. The high slope value at the high temperature is attributed to the large conduction band offset of the AlGaInAs quantum-well structure.

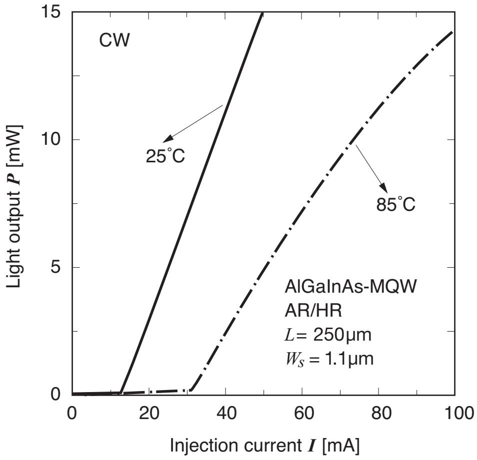

Fig. 3. Light output characteristics for a RWG DFB laser under the CW condition at 25 °C and 85 °C

We evaluated 14.0 Gbit/s and 25.8 Gbit/s output waveforms of the fabricated RWG DFB laser using non-return-to-zero (NRZ) signal having a $2^{31}-1$ pseudorandom bit sequence. The detuning of the laser was −1.7 nm. **photo 2** shows the 25.8 Gbit/s eye-diagram at 25 °C. The bias current was set at 50 mA, and the relaxation oscillation frequency (f_r) was 15 GHz in this bias condition. The clear eye-opening with the extinction ratio of 6 dB was successfully observed due to the wide electrical bandwidth by the RWG structure buried with BCB polymers. The rise time (t_r) and the fall time (t_f) were estimated to be 13 ps and 16 ps, respectively.

photo 3 shows 14.0 Gbit/s eye-diagrams at (a) 25 °C and (b) 85 °C. The bias currents at 25 °C and 85 °C were set at 40 mA and 60mA, respectively. The relaxation oscillation frequencies (f_r) in these bias conditions at 25 °C and 85 °C were 13 GHz and 11 GHz, respectively. As can be seen, 14.0 Gbit/s uncooled operation was achieved up to 85 °C when the extinction ratio was 5 dB.

We also carried out the accelerated lifetime test (aging temperature: 85 °C, injection current: 200 mA, the number of samples: 17) for fabricated RWG DFB lasers. As shown in **Fig. 5**, the stable operation was observed even

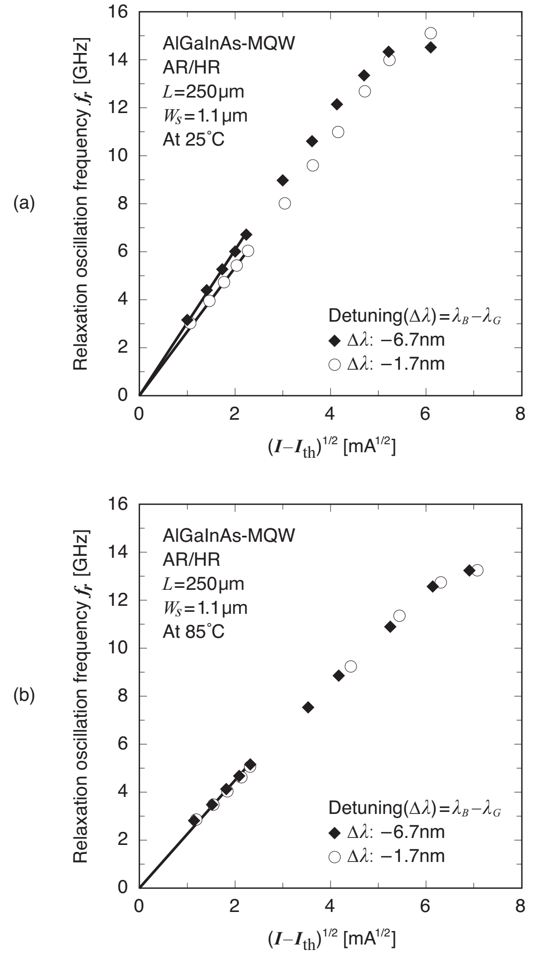

Fig. 4. Square root of bias current dependence of f_r for RWG DFB lasers at (a) 25 °C and (b) 85 °C

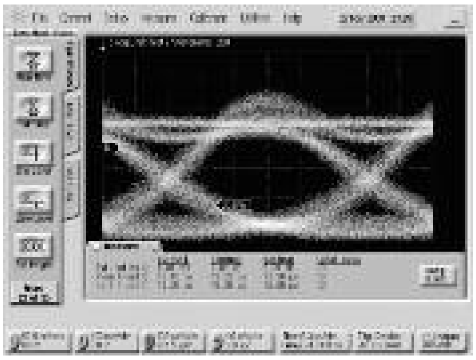

Photo 2. Eye-diagram under 25.8 Gbit/s direct modulation (Extinction ratio: 6 dB)

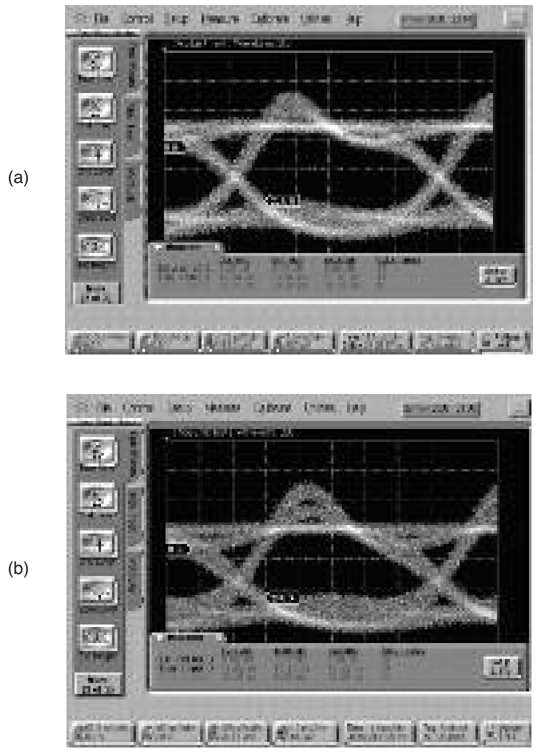

Photo 3. Eye-diagrams at (a) 25 °C and (b) 85 °C under 14.0 Gbit/s direct modulation (Extinction ratio: 5 dB)

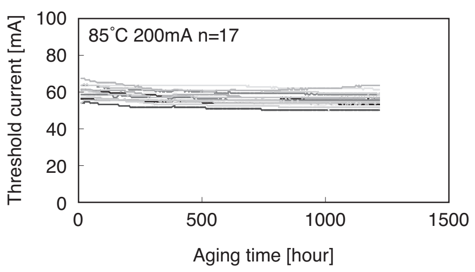

Fig. 5. Accelerated lifetime test for the RWG DFB laser buried by BCB polymers

after more than 1,200 hours. This result indicates that the AlGaInAs/InP RWG DFB laser fabricated using the BCB planarization process has the good reliability.

4. Conclusion

We fabricated 1.3 µm wavelength AlGaInAs/InP DFB lasers with the ridge-waveguide structure buried by BCB polymers. As a result, the clear eye-opening was observed under 26 Gbit/s direct modulation with the extinction ratio of 6 dB at 25 °C. Uncooled operation under 14 Gbit/s direct modulation with the extinction ratio of 5 dB was also achieved up to 85 °C.

From the accelerated lifetime test (200 mA, 85 °C), we confirmed the good reliability of the fabricated ridge-waveguide laser since the stable operation was observed even after more than 1,200 hours. Therefore, we demonstrated that ridge-waveguide lasers utilizing the BCB planarization process are very promising as a light source for high-speed transmitters used for over 10 Gbit/s applications.

References

(1) K. Nakahara, T. Tsuchiya, T. Kitatani, K. Shinoda, T. Kikawa, F. Hamano, S. Fujisaki, T. Taniguchi, E. Nomoto, M. Sawada, and T. Yuasa, "12.5-Gb/s Direct Modulation Up to 115 °C in 1.3-µm InGaAlAs-MQW RWG DFB Lasers With Notch-Free Grating Structure," J. Light. Technol., vol. 22, no. 1, pp. 159-165, Jan. 2004.

(2) K. Takagi, S. Shirai, Y. Tatsuoka, C. Watatani, T. Ota, T. Takiguchi, T. Aoyagi, T. Nishimura, and N. Tomita, "120 °C 10-Gb/s Uncooled Direct Modulated 1.3-µm AlGaInAs MQW DFB Laser Diodes," IEEE Photon. Technol. Lett., vol. 16, No. 11, pp. 2415-2417, Nov. 2004.

(3) N. Ikoma, T. Kawahara, N. Kaida, M. Murata, A. Moto, and T. Nakabayashi, "Highly Reliable AlGaInAs Buried Heterostructure Lasers for Uncooled 10Gb/s Direct Modulation," Optical Fiber Communication (OFC 2005), no. OThU1, Anaheim, CA, USA, Mar. 2005.

(4) R. Kobayashi, A. Ito, S. Kato, Y. Muroya, T. Koui, Y. Sakata, J. Shimizu, and S. Ishikawa, "Low Drive-Current and Wide Temperature Operation of 1.3-µm AlGaInAs-MQW BH-DFB Lasers by Laterally Enhanced Cladding Layer Growth," Optical Fiber Communication (OFC 2008), no. OThK2, San Diego, CA, USA, Feb. 2008.

(5) K. Otsubo, M. Matsuda, K. Takada, S. Okumura, M. Ekawa, H. Tanaka, S. Ide, K. Mori, and T. Yamamoto, "Uncooled 25 Gbit/s direct modulation of semi-insulating buried-heterostructure 1.3 µm AlGaInAs quantum-well DFB lasers," Electron. Lett., vol. 44, no. 10, pp. 631-632, May 2008.

(6) J. Wiedmann, M. M. Raj, K. Ebihara, K. Matsui, S. Tamura, and S. Arai, "Deeply etched semiconductor/benzocyclobutene distributed Bragg reflector laser combined with multiple cavities for 1.5-µm-wavelength single-mode operation," Jpn. J. Appl. Phys., vol. 40, part 1, no. 6A, pp. 4031-4037, Jun. 2001.

(7) H. Yagi, K. Miura, Y. Nishimoto, D. Plumwongrot, T. Maruyama, and S. Arai, "Low Threshold Current Density Operation of GaInAsP/InP DFB Lasers Consisting of Quantum-Wire Active Regions," International Conference on Quantum Electronics 2005 and the Pacific Rim Conference on Lasers and Electro-Optics 2005 (IQEC/CLEO-PR 2005), no. CTuJ1-4, pp. 61-62, Tokyo, Japan, Jul. 2005.

Contributors (The lead author is indicated by an asterisk (*)).

H. YAGI*

- Dr. Eng., Transmission Devices R&D Laboratories

He is engaged in the research and development of the fabrication process and the design of semiconductor lasers for optical communications.

Y. ONISHI

- Dr. Eng., Transmission Devices R&D Laboratories

K. KOYAMA

- Assistant Manager, Transmission Devices R&D Laboratories

Y. TSUJI

- Transmission Devices R&D Laboratories

H. ICHIKAWA

- Transmission Devices R&D Laboratories

H. YOSHINAGA

- Transmission Devices R&D Laboratories

N. KAIDA

- Assistant Manager, Transmission Devices R&D Laboratories

T. NOMAGUCHI

- Manager, Transmission Devices R&D Laboratories

K. HIRATSUKA

- Dr. Sc., Manager, Transmission Devices R&D Laboratories

K. UESAKA

- Manager, Transmission Devices R&D Laboratories