450 nm GaInN ridge stripe laser diodes with AlInN/AlGaN multiple cladding layers

Kei Arakawa1, Kohei Miyoshi1, Ryosuke Iida1, Yuki Kato1, Tetsuya Takeuchi1, Makoto Miyoshi2, Satoshi Kamiyama1, Motoaki Iwata1, and Isamu Akasaki1,3

1Faculty of Science & Engineering, Meijo University, Nagoya, Aichi, 468-8502 Japan
2Research Center for Nano Devices and Advanced Materials, Nagoya Institute of Technology, Nagoya, Aichi, 466-8555 Japan
3Akasaki Research Center, Nagoya University, Nagoya, Aichi, 464-8603 Japan

Received January 4, 2019; accepted March 19, 2019; published online May 23, 2019

We investigated and improved optical waveguides along the vertical and horizontal directions in 450 nm GaInN laser diodes. As a result, we demonstrated a low threshold current density (1.15 kA cm−2) of a GaInN ridge stripe laser diode containing a 3-pair 40 nm Al0.03Ga0.97N/25 nm GaInN/25 nm GaN multiple bottom cladding layer at room temperature under pulsed condition. This threshold current density is smaller than our typical value with a 1 μm Al0.03Ga0.97N bottom cladding layer. AlInN/AlGaN multiple layers are useful as n-type cladding layers in visible laser diodes to achieve higher optical confinement factors while smooth surfaces were obtained.© 2019 The Japan Society of Applied Physics

1. Introduction

Recently, there has been considerable attention given to visible GaInN multi-quantum well (QW) edge-emitting laser diodes (LDs) as novel light sources. In particular, blue and green LDs are demanded for compact laser projectors and laser displays.1–5 At the same time, fabrication of LDs emitting longer wavelengths are not straightforward because of low-quality active regions and a small relative refractive index difference, Δn/n, between waveguiding layers and cladding layers.5–10 In this paper, the waveguiding layer means a core layer of the waveguide which is inserted to form a core structure of QW lasers.

A typical edge-emitting LD contain optical waveguides along the vertical and horizontal directions. The vertical optical waveguide is mostly realized with a semiconductor epitaxial layer structure consisting of a bottom cladding layer, an intermediate waveguiding layer, and a top cladding layer. Conventional GaInN-based LDs11–14 contain GaN waveguiding and AlGaN cladding layers. Unfortunately, Δn/n between the GaN waveguiding layer and the AlGaN cladding layer is decreased with an increase of the emission wavelength.15 In order to obtain a sufficiently large Δn/n, an AlGaN cladding layer with a higher AlN mole fraction16–17 and a GaInN waveguiding layer with a higher InN mole fraction18–19 have been attempted; however, they resulted in poor crystal qualities due to their larger lattice mismatches. Another approach is a use of an AlInN cladding layer which is lattice-matched to GaN, showing a low refractive index value. Recently, room temperature (RT) pulsed operations of GaN edge-emitting LDs with n-AlInN bottom cladding layers have been demonstrated in order to leverage the low refractive index of AlInN. So far, relatively high threshold current densities (6.7–35 kA cm−2) have been reported from the LDs emitting relatively short wavelength regions, 394–415 nm.15–20–24 In the meantime, the horizontal optical waveguide is realized by forming a ridge stripe structure after the epitaxial growth.25–26 The ridge stripe structure is formed by patterning by photolithography and partly etching the top p-type layers above the QW active layer.

In this paper, we investigated and improved optical waveguides along the vertical and horizontal directions in GaInN LDs emitting 450 nm wavelength. Firstly, we utilized AlInN/AlGaN multiple bottom cladding layers in 450 nm GaInN LD structures and showed their superior device characteristics to those with standard AlGaN cladding layers. Secondly, we developed deep ridge stripe LDs for higher optical confinement factors in the horizontal direction. Finally, based on the above results, we demonstrated a 450 nm GaInN ridge stripe LD with the AlInN/AlGaN bottom cladding layers, showing a threshold current density of 1.15 kA cm−2.

2. Experiments

We prepared two sets of 450 nm GaInN ridge stripe LDs towards larger optical confinements along the vertical and horizontal directions. The first set of LD samples was formed to investigate the vertical optical confinement, and the second set of the LD samples were formed for the horizontal optical confinement. Finally, we fabricated a 450 nm ridge stripe LD based on the results of the above two investigations. All LD samples were grown on c-plane GaN substrates by metal organic vapor phase epitaxy.

LD structures in the first set had different bottom cladding layers. The LD layer structure contained bottom n-type cladding layers, an n-GaN/n-AlInN waveguide layer, GaInN/GaN two QWs emitting 450 nm wavelength, a p-GaN waveguide layer, a p-AlGaN electron blocking (EB) layer, a p-AlGaN cladding layer, and a p-GaN contact layer. The bottom cladding layers we investigated here were three types, such as a 1 μm n-Al0.03Ga0.97N, an n-type 3-pair 40 nm Al0.82In0.18N/25 nm Al0.03Ga0.97N multiple layers, and also an n-type hybrid structure, that is, the n-type 3-pair 40 nm Al0.82In0.18N/25 nm Al0.03Ga0.97N/GaInN/GaN two QWs emitting 450 nm wavelength, a p-GaN waveguide layer, a p-AlGaN electron blocking (EB) layer, a p-AlGaN cladding layer, and a p-GaN contact layer. The bottom cladding layers we investigated here were three types, such as a 1 μm n-Al0.03Ga0.97N, an n-type 3-pair 40 nm Al0.82In0.18N/25 nm Al0.03Ga0.97N multiple layers, and also an n-type hybrid structure, that is, the n-type 3-pair 40 nm Al0.82In0.18N/25 nm Al0.03Ga0.97N/GaInN/GaN two QWs emitting 450 nm wavelength, a p-GaN waveguide layer, a p-AlGaN electron blocking (EB) layer, a p-AlGaN cladding layer, and a p-GaN contact layer.
optical confinement factor by its low refractive index value. Thereby, a reduction of the threshold current density is expected. Recently a high-quality 300 nm-thick AlInN layer has been obtained,\textsuperscript{27) but here we used AlInN/AlGaN multiple layers which were similar to the AlInN/GaN distributed Bragg reflector that we already optimized and demonstrated.\textsuperscript{28,29)} The reason to use multiple layers is a higher reproducibility at this moment in order to obtain smooth surfaces by using thin AlGaN layers grown at a high growth temperature (1020 °C). At the same time, we decreased the thickness of AlGaN layers to 25 nm from the DBR case (45 nm) to minimize a reduction of an average refractive index value of the cladding layer. Mg and Si were used to form p-type and n-type layers. Note that we also prepared a test structure, that is, the n-type 3-pair AlInN/AlGaN multiple layers on the GaN substrate, in order to evaluate a surface morphology and a vertical resistance. Ti/Al/Ti/Au electrodes were used for the vertical resistance measurement.

We then fabricated ridge stripe LDs with cavity lengths of 0.8, 1.2, and 1.5 mm, a ridge width of 10 μm, and a ridge height of 250 nm from the three LD wafers. Cleaved facets without any coating were used as cavity mirrors. Current density-light output power (J-L) characteristics and emission spectra of the LDs were measured at RT under pulsed condition (pulse width: 10 μsec, duty ratio: 1%).

The second set of the samples were ridge stripe LDs with 1 μm n-Al\textsubscript{0.03}Ga\textsubscript{0.97}N cladding layers [shown in Fig. 1(a)] in
which the ridge heights were varied from 250 to 490 nm, as shown in Fig. 3, in order to investigate horizontal optical confinements. The cavity length was 1.0 mm, and the ridge width was 10 μm. Cleaved facets without any coating were used as cavity mirrors. ITO electrodes for the p-side and Cr/Pt/Au electrodes for the n-side were used. J-L characteristics and far field patterns (FFPs) of LDs were measured at RT under the same pulsed condition mentioned above.

We also calculated possible modes and the corresponding horizontal effective refractive index values as a function of the ridge height. Note that we used vertical effective refractive indices at the ridge region and the etched region to calculate Δn/n values with the three ridge heights. FWHM values of FFPs in the modes were also calculated to compare the measured values.

Finally, we fabricated a 450 nm GaInN ridge stripe LDs with three-pair AlInN/AlGaN multiple cladding layers. The cavity lengths were 0.8, 1.2, and 1.5 mm. A ridge width and height were 15 μm and 490 nm. Not only J-L but also J-voltage (J-V) characteristics and emission spectra of LDs were measured at RT under the same pulsed condition.

3. Results and discussion

Figures 4(a) and 4(b) show an atomic force microscopy (AFM) image and J-V characteristics under vertical injection of n-type three-pair AlInN/AlGaN multiple layers. The AlInN/AlGaN surface was very smooth, showing a 0.14 nm RMS value. In addition, an ohmic behavior was obtained in the J-V characteristics under vertical current injection from an electrode on the surface to that on the back side of the GaN substrate. After successfully obtaining the above characteristics, the AlInN/AlGaN layers were incorporated in LD structures.

The J-L characteristics and the emission spectra of LDs with n-AlGaN. The n-AlInN/AlGaN, and the hybrid layers as bottom cladding layers are shown in Figs. 5(a)–5(c), respectively. The lasing wavelengths of all the LDs were around 450 nm as shown in the insets of Fig. 5. All the threshold current densities were decreased with an increase of the cavity length. We then summarized all the values of the threshold current densities as a function of the cavity length in Fig. 6. LDs containing AlInN/AlGaN multiple cladding layers showed lower threshold current densities in all the cavity length cases. For example, at 1.5 mm cavity length, 1.5 kA cm$^{-2}$ was obtained with the AlInN/AlGaN and 1.7 kA cm$^{-2}$ was obtained without the AlInN/AlGaN. We calculated optical confinement factors (Γ) of the three LD structures along the vertical direction. The Γ values at 450 nm were 1.54% with the AlGaN and 1.84% with the AlInN/AlGaN or the hybrid structure. The 19% larger Γ value was obtained due to the lower refractive index of AlInN. The lower threshold current densities with AlInN/AlGaN could be due to the larger Γ mentioned above. Note that in order to achieve the same optical confinement factor value just by a single AlGaN cladding layer, at least a 45% AlN mole fraction is necessary, suggesting a poor crystalline quality due to a huge tensile strain during epitaxial growth. Furthermore, the situation is more pronounced for longer wavelength. A larger difference (24%) in Γ was obtained at an emission wavelength of 530 nm even with the same structures (1.39% with AlGaN and 1.73% with AlInN/AlGaN). Thus, AlInN cladding layers should be useful for the long-wavelength GaN edge-emitting layer diodes.

Next, Fig. 7(a) shows the J-L characteristics of ridge stripe LDs with different ridge heights. In order to evaluate a linearity of the J-L curves, we then modified J-L characteristics to the external differential quantum efficiency, $\eta_{\text{ext}}$, as a function of the current density in Fig. 7(b). While all the LDs showed about 30% $\eta_{\text{ext}}$ from the one facet, a better linearity in the $\eta_{\text{ext}}$ was obtained with an increase of the ridge height. Then FFPs of the LDs with the different ridge heights were also measured at a current density of a threshold value plus 4.0 kA cm$^{-2}$ and plotted in Fig. 8(a). FWHMs of FFPs of the
LDs with ridge heights of 250 nm, 380 nm and 490 nm were 7°, 16° and 23°, respectively. A higher ridge resulted in a wider FWHM of the FFP. We then calculated the FWHM of the FFPs. Figure 8(b) shows calculated horizontal effective refractive indices of all the possible modes as a function of the ridge height. Number of modes was increased with an increase of ridge height. For example, the ridge height of 490 nm corresponding to a $\Delta n/n$ of 0.6% led to 13 modes. Then we calculated all FWHM values of the FFP in the possible modes (4, 8, and 13 modes for 250, 380, and 490 nm ridge heights, respectively). We eventually plotted the calculated FWHM values of the FFPs in all the possible modes, shown with dots in Fig. 8(c). The measured FWHM values in Fig. 8(a) are also indicated by the lines in Fig. 8(c). The measured FWHM values (7, 16, and 23°) were less than the maximum calculated values (10, 21, and 34°) along with the ridge height. The results suggest that the wider FWHM obtained in a higher ridge stripe LD was attributed to the higher-order mode operation, in which light could be well confined due to the higher ridge. Thus, we conclude that the better linearity in the differential quantum efficiency was achieved by not a simple single mode operation but many successive mode transitions from a mode to the next higher-order mode, leading to smooth transitions. Note that the $\eta_{\text{ext}}$ values were obtained from only one facet of the LDs, thus the actual $\eta_{\text{ext}}$ values were about 60%.

Finally, we measured J-V-L characteristics and emission spectra of a 450-nm GaInN ridge stripe LDs with the 3-pair AlInN/AlGaN multiple cladding layers at RT under the same pulsed condition, and then plotted in Fig. 9. The LD layer structure was the same as that in Fig. 1(b). The ridge height was 490 nm, the cavity lengths were 0.8, 1.2, and 1.5 mm, and the ridge width was 15 $\mu$m. Cleaved facets without any
Fig. 7  (Color online) (a) J-L characteristics and (b) $\eta_{\text{ext}}$ characteristics of ridge stripe LDs with different ridge heights from 250 nm to 490 nm.

Fig. 8.  (Color online) (a) Measured FFPs of ridge stripe LDs with different ridge heights, (b) calculated effective refractive index values of all the possible modes along the horizontal direction as a function of ridge height, and (c) calculated FWHMs of FFPs as a function of mode number.
coating were used. Note that the above LD contained the improved vertical and horizontal waveguide structures in the above investigations. Lasing wavelengths of the LDs were improved vertical and horizontal waveguide structures in the coating were used. Note that the above LD contained the AlInN/AlGaN multiple layers. The ridge height and width were 490 nm and 15 μm, respectively.

4. Conclusions

In this study, we found that the 3-pair Al0.82In0.18N/Al0.03Ga0.97N bottom cladding layers were useful for a reduction of a threshold current density compared to the Al0.03Ga0.97N cladding layer in the 450 nm GaInN ridge stripe LDs. The AlInN/AlGaN multiple layer provided a low refractive index value as well as a smooth surface. In addition, ηext showed a better linearity in the J-L characteristics with an increase of the ridge height. We conclude that the better linearity of the ηext was achieved by not a simple single mode operation but many successive mode transitions from a mode to the next higher-order mode. Finally, we demonstrated the GaInN ridge stripe laser diode with bottom AlInN cladding layers, showing a threshold current density of 1.15 kA cm$^{-2}$ at RT under pulsed condition. The lasing wavelength was 450 nm. However, the device resistance with the AlInN/AlGaN layers was high, 4.4 Ω, corresponding to a resistivity of 9.9 × 10$^{-4}$ Ωcm², which requires further improvements.

Acknowledgments

This work was supported by MEXT Program for research and development of next-generation semiconductor to realize energy-saving society, MEXT Private University Research Branding Project, JSPS KAKENHI for Innovative Areas [16H06416].

ORCID iDs

Kei Arakawa https://orcid.org/0000-0002-5699-4193

Fig. 9. (Color online) J-V-L characteristics and emission spectra (inset) of a ridge stripe LD with the AlInN/AlGaN multiple layers. The ridge height and width were 490 nm and 15 μm, respectively.

1) M. Jansen et al., Proc. SPIE 6135, 61350T (2006).
2) D. Queren, M. Schillgalieis, A. Avramescu, G. Brüderl, A. Laubsch, S. Lutgen, and U. Strauß, J. Cryst. Growth 311, 2933 (2009).
3) S. Lutgen, A. Avramescu, T. Lerner, M. Schillgalieis, D. Queren, J. Müller, D. Demi, A. Breidenassel, and U. Strauss, Proc. SPIE 7616, 76160G (2010).
4) U. T. Schwarz and W. G. Scheibenzuber, Opt. Photonics News 22, 38 (2011).
5) D. Sizov, R. Bhat, and C. E. Zaf, J. Lightwave Technology 30, 679 (2012).
6) Y. H. Cho, G. H. Guiner, A. J. Fischer, J. J. Song, S. Keller, U. K. Mishra, and S. P. DenBaars, Appl. Phys. Lett. 73, 1370 (1998).
7) R. A. Oliver, M. J. Kappers, C. J. Humphreys, G. Andrew, and D. Briggs, J. Appl. Phys. 97, 013707 (2005).
8) J. Bai, T. Wang, and S. Sakai, J. Appl. Phys. 88, 4729 (2000).
9) L. Q. Zhang, D. S. Jiang, J. J. Zhu, and D. G. Zhao, J. Appl. Phys. 105, 023104 (2009).
10) J. Yang et al., Opt. Express 24, 13824 (2016).
11) Y. Cheng et al., Appl. Phys. Lett. 109, 092104 (2016).
12) A. Tian et al., Opt. Express 25, 415 (2017).
13) S. Mehari, D. A. Cohen, D. L. Bercera, S. Nakamura, and S. P. DenBaars, Opt. Express 26, 1564 (2018).
14) A. Myzafferi, A. J. Mughal, D. A. Cohen, R. M. Farrell, S. Nakamura, J. S. Speck, and S. P. DenBaars, Opt. Express 26, 12490 (2018).
15) T. Lerner et al., Phys. Stat. Sol. (a) 207, 1328 (2010).
16) H. Y. Ryu, K. H. Ha, J. K. Son, H. S. Paek, Y. J. Sung, K. S. Kim, H. K. Kim, Y. Park, S. N. Lee, and O. H. Nam, J. Appl. Phys. 105, 103102 (2009).
17) C. Y. Huang, Y. D. Lin, A. Tyagi, A. Chakrabarty, H. Ohla, J. S. Speck, S. P. DenBaars, and S. Nakamura, J. Appl. Phys. 107, 013101 (2009).
18) K. M. Kelchner, Y.-D. Lin, M. T. Hardly, C. Y. Huang, P. S. Hu, R. M. Farrell, D. A. Haeger, H. C. Kuo, F. Wu, and K. Fujito, Appl. Phys. Express 2, 071003 (2009).
19) J. Lingrpong, L. Jianping, T. Aqin, C. Yang, L. Zengcheng, Z. Liuan, Z. Shuming, L. Deyao, M. Ikeada, and Y. Hui, J. Semicond. 37, 111001 (2016).
20) A. Castiglia, E. Feldin, J. Dorsaz, G. Cosendey, J. F. Carlin, R. Butte, and N. Grandjean, Electoron. Lett. 44, 8 (2008).
21) A. D. Drager, H. Jonen, H. Bremers, U. Rossow, P. Demolon, H. P. D. Schenk, J. Y. Duboz, B. Corbett, and A. Hangleiter, Phys. Stat. Sol. (c) 6, 5704 (2009).
22) W.-S. Tan, K. Takahashi, V. Bouquet, A. Ariyoshi, Y. Tsuda, M. Ohta, and M. Kauer, Appl. Phys. Express 2, 112101 (2009).
23) A. Castiglia, E. Feldin, G. Cosendey, A. Althoukov, J. F. Carlin, R. Butte, and N. Grandjean, Appl. Phys. Lett. 94, 193506 (2009).
24) R. Charsingh et al., Appl. Phys. Lett. 98, 12 (2011).
25) S. Itou et al., Sharp Technical Report 77, 53 (2000).
26) Y. Takiguchi, T. Asatsuma, and T. Hirao, Jpn. J. Opt. 37, 172 (2008).
27) M. Miyoshi, M. Yamamaku, T. Egawa, and T. Takauchi, Appl. Phys. Express 11, 051001 (2018).
28) Y. Kozuka, K. Ikaeuma, T. Yasuda, T. Takeuchi, S. Kamiyama, M. Iwaya, and I. Akasaki, MRS Fall Meeting, 2014MRSF14-1736-T13-08.R1.
29) T. Takeuchi, S. Kamiyama, M. Iwaya, and I. Akasaki, Rep. Prog. Phys. 82, 012502 (2018).
30) M. Maruyama, Y. Nakayama, K. Yamazaki, Y. Hoshina, H. Watanabe, N. Fuittagawa, H. Kawanishi, T. Uemura, and H. Narui, Phys. Stat. Sol. (a) 215, 1700513 (2018).
31) Y. Nakatsu, Y. Nagao, K. Kozuru, T. Hirao, E. Okahisa, S. Masui, T. Yamamoto, and S. Nagahama, The Int. Society for Optical Engineering, San Francisco, CA, USA, 2019.