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Milliwatt-class Green and Blue GaN-based Vertical-Cavity Surface-Emitting Lasers

Kenichi Terao, Hitoshi Nagai, Daisuke Morita, Shingo Masui, Tomoya Yanamoto, Shin-ichi Nagahama

kenichi.terao@nichia.co.jp
Nichia Corporation, 491 Oka, Kaminaka-cho, Anan-shi, Tokushima 774-8601, Japan
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ABSTRACT

We demonstrated a room-temperature continuous-wave operation of the single-mode green and blue VCSELs with epitaxially grown AlInN/GaN DBRs. Our blue VCSELs show the highest wall-plug efficiency of 13.6%, stable CW operation, and a high yield. Furthermore, our green VCSELs also provide the highest optical output power exceeding 1.5 mW and wall-plug efficiency of 3.7%.

1 Introduction

Gallium nitride (GaN)-based laser diodes have achieved great success in display applications so far. This is due to some key advantages for using laser diodes as light sources compared with conventional lamps or LED: wide color reproduction, high power and high luminance, small spot size, high-speed modulation, etc. Currently, watt-class high-power blue and green GaN-based edge-emitting laser diodes are commercially available and are mainly used in laser projectors or laser TVs [1].

Meanwhile, there are also increasing demands for low power lasers for use in augmented reality (AR) smart glasses recently. Such glasses may feature a retinal scanning display, with red, green and blue beams of light guided by a scanning MEMS mirror to project an image directly into the eye. To ensure eye safety, a low optical output laser (e.g. a few milliwatt or less) is suitable for this application. A potential candidate for the light source of a retinal scanning display is thought to be a vertical-cavity surface-emitting laser (VCSEL) [2] rather than a conventional edge-emitting laser due to its features of low threshold current and low output power. The lower threshold current, which benefits AR glasses by reducing power consumption and lengthening battery life, comes from the smaller emission volume of a VCSEL. In a single transverse-mode VCSEL, an aperture diameter is typically 5 μm, and an active layer thickness is around 20 nm, resulting in the emission volume of 0.4 μm^3. Meanwhile, a single transverse-mode edge-emitting laser has the emission volume of around 4 μm^3 (for a device with 200 μm cavity length, 2 μm ridge width, and 10 nm active layer thickness). This small emission volume of a VCSEL leads to the reduction of the threshold current compared to that of an edge-emitting laser. Another feature for a VCSEL is the peak power saturation at lower power than an edge-emitting laser, which is due to self-heating effect. This low output power limitation of a VCSEL ensures the eye safety.

Until now, AlInGaP-based red VCSELs have already been commercialized; however, GaN-based blue and green VCSELs are still under development and have not been commercialized yet. For the development of full-color projectors for AR glasses, the practical realization of blue and green VCSELs is required.

In 2008, Nichia reported the first demonstration of room-temperature (RT) lasing of violet GaN-based VCSELs by continuous-wave (CW) current injection [3][4], followed by blue (RT, CW) and green (RT, pulse) VCSELs in 2011 [5][6]. These studies have with no doubt made a great contribution to the subsequent studies on GaN-based VCSELs; however, the fabrication process adopted at that time had a problem, making it incompatible with mass production. Those VCSELs were composed of a pair of dielectric DBRs and required a wafer polishing process to remove a GaN substrate and form the cavity of around 1 μm thickness. This cavity length must be controlled with a nanometer scale accuracy, however, instability of the polishing rate made the sufficient control of cavity length difficult. Hence the characteristics of them were unstable and acceptable yield was not obtained.

2 Structure

To avoid this problem, we have turned to a design that combines a dielectric top mirror with a bottom mirror based on an $Al_{0.8}In_{0.2}N$/GaN epitaxially grown DBR. Nitride-based epitaxial DBRs have recently been developed for use as a mirror in VCSELs (i.e. AlGaN/GaN [7], AlN/GaN [8] and AlInN/GaN [9] pairs). Among them, an $Al_{0.8}In_{0.2}N$/GaN DBR is especially suitable for a GaN-based VCSEL because the in-plane lattice constant of $Al_{0.8}In_{0.2}N$ is matched to that of GaN, therefore it can function as a defect-free highly reflective mirror.

By introducing such an epitaxial mirror as a bottom side DBR, a cavity part, consisting of *p-i-n* layers, can be grown monolithically following the epitaxial DBR layers by metal organic chemical vapor deposition (MOCVD). This approach is far simpler than the way using wafer polishing and enables more precise control over the cavity length, then it may be more suited to mass production.

During the past decade, there have been many reported studies on blue VCSELs with an AlInN/GaN DBR, however, the threshold current of them has been still high, exceeding 1 mA. Moreover, there have not been any reports for the study on a green VCSEL with an AlInN/GaN DBR until now. In order to produce high-efficient GaN-based green and blue VCSELs, we have optimized the epitaxial layers and device structures, then we have made significant advances with them - the milliwatt-class optical output power and the highest ever reported wall-plug efficiency [10].

The schematic structure of our blue and green VCSEL chips is shown in Figure 1. The epitaxial structures including $Al_{0.8}In_{0.2}N$/GaN epitaxial DBR, *n*-type, active and *p*-type layers were grown by MOCVD on a 2-inch *c*-plane free-standing GaN substrate. After the epitaxial growth, a circular current confinement region was formed by passivating the *p*-GaN surface, and an indium tin oxide (ITO) transparent electrode was deposited. Subsequently, a *p*-pad and a *n*-electrode were fabricated, followed by a Nb_2O_5 spacer layer and a SiO_2/Nb_2O_5 dielectric DBR. Total thickness corresponds to a 4.5λ cavity length, which is short enough for single longitudinal mode lasing because the longitudinal mode spacing in the case of the 4.5λ cavity is wider than the gain spectrum width of the active layer. After the process steps mentioned above, the back surface of the GaN substrate was polished and coated with an anti-reflection (AR) coating. Finally, VCSEL chips were diced and mounted on a heatsink using a junction down method in a TO-CAN package for suppressing thermal resistance. Optical output power was monitored from the AlInN/GaN DBR side.

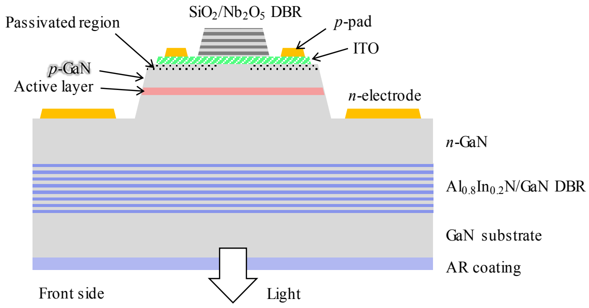

Figure 1. Schematic structure of the single-mode blue and green VCSELs.

3 Results

Figure 2 shows optical output power-current (L-I) and the voltage-current (V-I) characteristics of the blue VCSEL under CW operation at a case temperature of 25 ºC. The threshold current and the threshold voltage was 0.40 mA (J_{th} = 3.2 kA/cm^2) and 3.75 V respectively, which are relatively low values for blue VCSELs. Additionally, the optical output power is more than 2 mW. The maximum wall-plug efficiency was 13.6% at 2.6 mA, which is the highest ever reported value for blue VCSELs.

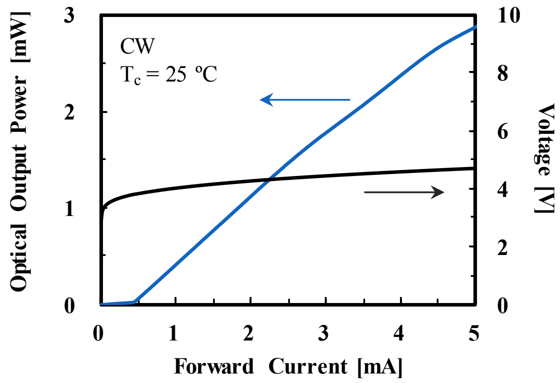

Figure 2. L-I and V-I characteristics of the blue VCSEL under CW operation at 25 ºC.

Figure 3 shows the emission spectra of the blue VCSEL under 1 mA, 3 mA, and 5 mA CW operation at a case temperature of 25 ºC. The peak wavelength of the blue VCSEL was 442.3 nm at 1 mA and the peak wavelength was slightly red-shifted as the forward current increased due to the refractive index change by self-heating (0.11 nm/mA). Each emission spectrum has a single peak, indicating that the blue VCSEL is oscillating with a single longitudinal and single transverse mode.

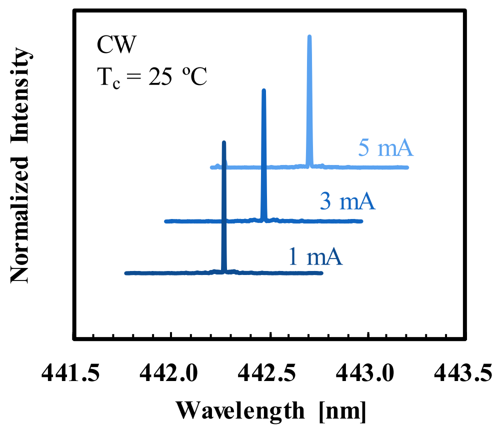

Figure 3. The emission spectra of the blue VCSEL under 1 mA, 3 mA and 5 mA CW operation at 25 ºC. Vertical axis has some offset for clarity.

Figure 4 shows the near-field pattern (NFP) of the blue VCSEL observed from the front side under 3 mA CW operation at a case temperature of 25 ºC. A fundamental transverse mode ($LP_{0,1}$ mode) was observed and the beam diameter was 1.5 μm (FWHM). The fundamental transverse mode was maintained at least up to 7 mA. The stable single transverse mode operation may be suitable for AR glass applications.

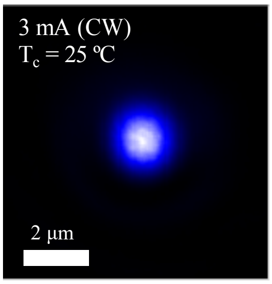

Figure 4. NFP image of the blue VCSEL emitted from the front side under 3 mA CW operation at 25 ºC.

In general, the operating current density of a GaN-based VCSEL is several tens of kA/cm^2, which is higher than that of an edge-emitting laser. This causes a decrease in the reliability of GaN-based VCSELs, and indeed only a few studies have reported on the reliable operation of them so far. In this work, we confirmed the reliability of the blue VCSELs. Figure 5 shows the lifetime test result for the blue VCSEL chips under automatic power control (APC) of 1.0 mW CW operation at 25 ºC, revealing stable operation of them for 500 hours.

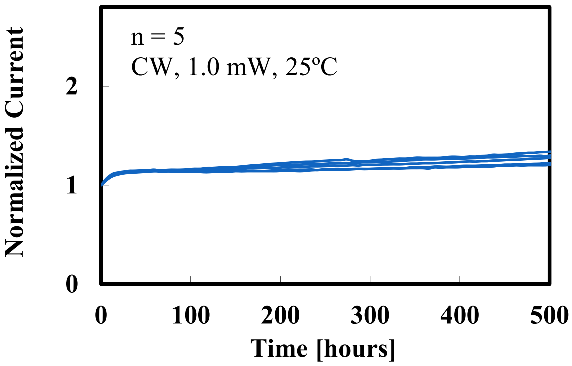

Figure 5. Lifetime test results of the blue VCSEL chips under APC of 1.0 mW CW operation at 25 ºC. Operating current is normalized by initial value.

We have also demonstrated high yield for these blue VCSEL chips. To oscillate a VCSEL, the resonant wavelength must be included in the range of the stopband of the DBRs within which the reflectivity is over 99%. However, the stopband width of an AlInN/GaN epitaxial DBR is relatively narrow compared to that of a dielectric DBR such as a SiO_2/Nb_2O_5 DBR, therefore controlling the thickness and composition of an AlInN/GaN DBR is important to make the stopband range stable. By optimizing the growth condition of an AlInN/GaN epitaxial DBR and customizing the MOCVD system, we have successfully achieved high yield for these blue VCSEL chips. Figure 6 shows the threshold current mapping of the blue VCSELs in a 2-inch wafer. We defined the effective area as the inside of a circle with a diameter of 44 mm, the reason for this is that the photolithography patterning at the edge of a wafer is unstable. In this case, the yield in the effective area is calculated to over 90% at the average threshold current of 1 mA. This suggests that the fabrication process of blue VCSELs with an AlInN/GaN DBR can meet mass production requirements.

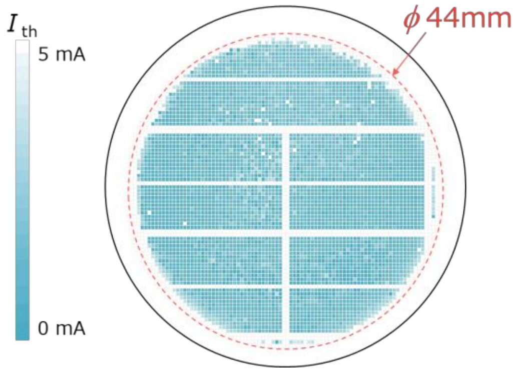

Figure 6. The threshold current mapping of the blue VCSELs in a 2-inch wafer. Some blank lines correspond to test element group (TEG) areas, where a VCSEL chip was not fabricated.

The development of a green VCSEL is a more challenging task than a blue VCSEL. One obstacle is the degradation of the quantum well at a higher indium content, and another is the decrease of optical gain in the long wavelength region, associated with the quantum-confined Stark effect. So far, some groups have reported green VCSEL lasing; however, the optical output power was still low (from several μW to several tens of μW) and the threshold voltage remained high; therefore, the wall-plug efficiency of GaN-based green VCSELs have been less than 0.1%. This inhibits the practical use of green VCSELs in commercial applications.

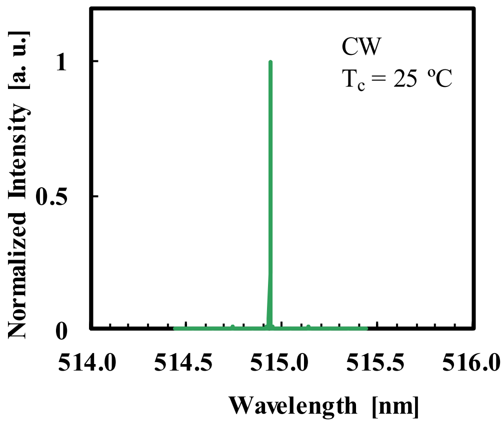

Figure 7. The emission spectrum of the green VCSEL under 4.8 mA CW operation at 25 ºC.

In this work, we have also succeeded in fabricating the high-performance single-mode green VCSELs. Figure 7 shows that the peak wavelength of the green VCSEL was 514.9 nm at the forward current of 4.8 mA under CW operation at 25 ºC. Its emission spectrum has a single peak; therefore, it was lasing with a single-longitudinal and single-transverse mode just like our blue ones. Figure 8 shows the threshold current was 2.8 mA (J_{th} = 14.3 kA/cm^2), and the threshold voltage was 5.02 V. The maximum output power was over 1.5 mW, which is more than one order of magnitude higher than that of previously reported green VCSELs. In addition, the wall-plug efficiency reached 3.7% at 7 mA, which is the highest ever reported value for nitride-based green VCSELs. The NFP for the green VCSEL, shown in Figure 9, was the fundamental transverse mode (LP0,1 mode).

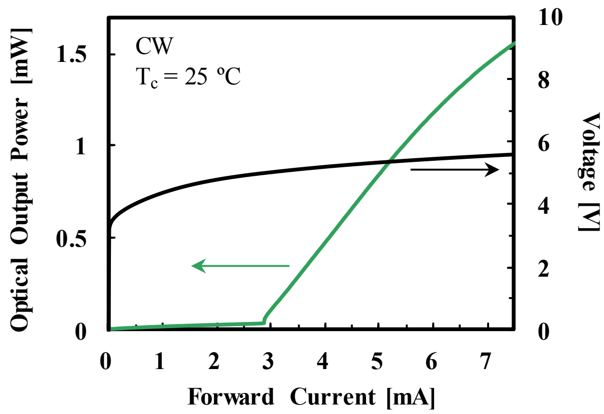

Figure 8. L-I and V-I characteristics of the green VCSEL under CW operation at 25 ºC.

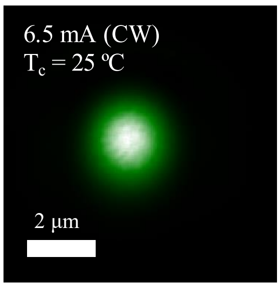

Figure 9. NFP image of the green VCSEL emitted from the front side under 6.5 mA CW operation at 25 ºC.

4 Conclusions

In this study, we have made considerable progress in the development of green and blue VCSELs. These VCSELs show milliwatt-class optical output power and the highest wall-plug efficiency among the previously reported values. This fabrication process of introducing an AlInN/GaN epitaxial DBR is suitable for mass production since it does not require extra process steps for cavity thickness control. We are expecting these results will enhance the feasibility of full-color projector applications with red, green and blue VCSELs.

As our future tasks, further improvement of the wall-plug efficiency of green and blue VCSELs would be required because they are still low compared to that of nitride-based edge-emitting lasers. In addition, extending the emission wavelength of the green VCSEL to the longer region is also needed to provide a wide color gamut. We will strive to further develop the blue and green VCSEL devices to put them into practical use in the near future.

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