High-output power and high-temperature operation of blue GaN-based vertical-cavity surface-emitting laser

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High output power values of 15.7 mW at 20 °C and 2.7 mW at 110 °C were obtained from a blue GaN-based vertical-cavity surface-emitting laser (VCSEL) under continuous-wave operation as a result of introducing a long-cavity (10λ) structure. The threshold current and voltage at 20 °C were 4.5 mA and 5.1 V, respectively. Owing to the reduced thermal resistance provided by the long-cavity structure and the adjusted reflectivity of the front cavity mirror, this VCSEL also exhibited a high slope efficiency of 0.87 W/A, a differential quantum efficiency of 31%, and a wall-plug efficiency of 8.9%. © 2018 The Japan Society of Applied Physics

Fig. 1. Schematic of the fabricated blue VCSEL.
reflectivity of the 10.5-pair SiO$_2$/Nb$_2$O$_5$ DBR. The measured reflectivity values of the 41-pair and 42-pair AlInN/GaN DBRs were 99.1 and 99.3%, respectively. VCSEL chips with an 8 μm aperture were subsequently mounted on a Cu heat sink block with a p-side-down (flip-chip bonding) configuration and operated under CW conditions.

Figure 2(a) shows the $I$--$L$--$V$ characteristics of the fabricated VCSEL with a 5λ-cavity structure in the case-temperature range from 20 to 100 °C. These data confirm that the device exhibited high-temperature lasing operation up to 100 °C. The threshold current ($I_{th}$), threshold current density, and threshold voltage at 20 °C were 4.2 mA, 8.4 kA/cm$^2$, and 5.1 V, respectively. The value of $I_{th}$ was slightly higher than that in our previous report$^{15}$ because the front mirror loss was higher owing to the lower reflectivity of the front mirror. To achieve high output power and efficiency, we reduced the reflectivity of the front mirror even though the threshold current was increased.$^{15}$ In Fig. 2(a), the maximum output power was 8.2 mW at an operating current of 20 mA, owing to a high slope efficiency ($\eta_s$) of 0.71 W/A and a differential quantum efficiency ($\eta_d$) of 25.4%. The maximum output power of the device was limited by thermal rollover, and both the operating current at rollover and the maximum output power were decreased at high heat-sink temperatures. Thus, a low $R_{th}$ was expected to allow operation at a relatively high current at rollover, giving an elevated output power over a wide temperature range.

Figure 2(b) summarizes the $I$--$L$--$V$ characteristics of the VCSEL with the 10λ-cavity structure over the temperature range from 20 to 110 °C. It is apparent that both the maximum output power and the operating current at rollover were dramatically enhanced by introducing the 10λ-cavity structure. An increased output power of 15.7 mW together with a high $\eta_d$ of 31% and an $\eta_s$ of 0.87 W/A were achieved at 20 °C. The threshold current, threshold current density, and threshold voltage at 20 °C were 4.5 mA, 9.0 kA/cm$^2$, and 5.1 V, respectively. Compared with the 5λ-cavity device, the operating current at rollover was significantly enhanced from 20 to 29 mA at 20 °C, likely due to a reduction in $R_{th}$, while the slope efficiency was also enhanced by reducing the reflectivity of the front cavity mirror.$^{15}$ These improvements resulted in an approximately doubled light output power at 20 °C. The maximum wall-plug efficiency at 20 °C was estimated to be 8.9% for the 10λ-cavity VCSEL and this device exhibited a higher lasing temperature up to 110 °C, at which an output power of 2.7 mW was obtained [as shown in Fig. 2(b)]. To the best of our knowledge, the output power of 15.7 mW, the differential quantum efficiency of 31%, and the operating temperature of 110 °C obtained from this unit are the highest values yet reported for a GaN-based VCSEL under CW operation.

Figures 2(a) and 2(b) show the emission spectra of the fabricated VCSELs with 5λ- and 10λ-cavity structures at various current injection levels of 0.9$I_{th}$, 0.95$I_{th}$, $I_{th}$, and 1.05$I_{th}$, respectively. The peak intensities were markedly increased above the threshold in both Figs. 3(a) and 3(b). The lasing wavelengths with a narrow linewidth of 0.08 nm were 443.5 and 440.1 nm for the VCSELs with 5λ- and 10λ-cavity structures under CW operation at 20 °C, respectively.

The effect of reducing $R_{th}$ by introducing a long-cavity structure was evaluated by assessing the $R_{th}$ of the device, which is typically determined experimentally using the equation

$$R_{th} = \frac{\Delta T}{\Delta P_{diss}} = \frac{\Delta \lambda/\Delta P_{diss}}{\Delta \lambda/\Delta T_{th}},$$

(1)

following the measurement of variations in the wavelength shift with changes in the dissipated power ($\Delta \lambda/\Delta P_{diss}$) and with changes in the heat-sink temperature ($\Delta \lambda/\Delta T_{th}$).$^{21-24}$ The reported $\Delta \lambda/\Delta T_{th}$ values for GaN-based VCSELs range from 0.012 to 0.0185 nm/K.$^{21,22,24,25}$ In this work, $\Delta \lambda/\Delta T_{th}$ values were acquired under pulsed operation to prevent the thermal effect, and the results obtained for VCSELs with 5λ- and 10λ-cavity structures were 0.0142 and 0.0146 nm/K, respectively. These are comparable to the literature values. The $\Delta \lambda/\Delta P_{diss}$ values determined for the VCSELs having 5λ- and 10λ-cavity structures were 0.015 and 0.0103 nm/mW, respectively. Using Eq. (1), the $R_{th}$ values were calculated to...
be 1100 and 710 K/W for the 5λ- and 10λ-cavity VCSELs, respectively. This 65% improvement indicates that the operating current at rollover in Figs. 2(a) and 2(b) was enhanced by a factor of approximately 1.5. As an example, the operating current at rollover was increased from 20 to 29 mA at 20 °C to give a ratio of 1.45. These results confirm that reducing $R_{th}$ leads to a higher output power. Compared with the results of the theoretical analysis of the $R_{th}$ values in Ref. 22, the impact of the $R_{th}$ reduction was quite reasonable, indicating that a thicker n-GaN layer essentially improves the thermal dissipation in our VCSEL structure.\(^\text{22}\)

The internal temperatures at rollover ($T_{\text{rollover}}$) were estimated to be 159 and 161 °C for the 5λ- and 10λ-cavity VCSELs using the respective $R_{th}$ and dissipated power values at rollover. These similar $T_{\text{rollover}}$ values also suggest that the reduced $R_{th}$ was the primary reason for the higher output power observed for the 10λ-cavity VCSEL. Thus, both $T_{\text{rollover}}$ and $R_{th}$ are important with regard to establishing the maximum lasing temperature ($T_{\text{max}}$). Under the lasing condition, this temperature can be expressed as

$$T_{\text{max}} < T_{\text{rollover}} - R_{th} \times P_{\text{diss}} \approx T_{\text{rollover}} - R_{th} \times I_{th} \times V_{th},$$

where $P_{\text{diss}}$ is the dissipated power at the threshold, $I_{th}$ is the threshold current, and $V_{th}$ is the threshold voltage. Thus, the temperature dependence of $I_{th}$ is also important in determining $T_{\text{max}}$. Figure 4 shows plots of the effects of temperature on the threshold currents of the fabricated VCSELs. These data demonstrate that, over the temperature range from 293 to 333 K, the temperature dependence of $I_{th}$ was minimal, and a relatively high characteristic temperature ($T_0 = 316$ K) was obtained in the case of the 10λ-cavity VCSEL. In contrast, $I_{th}$ rapidly increased with increasing temperature above 330 K. This tendency led to a significant internal temperature increase in the VCSELs below the threshold within the high-temperature region, resulting in the maximum lasing temperature of 110 °C observed for our device. The threshold current in VCSELs is governed by the mismatch between the wavelength of the cavity mode and the peak gain. Therefore, temperature-induced detuning of the lasing mode should be optimized in accordance with the requirements of each application.\(^\text{26}\)

In conclusion, we have demonstrated the highest output power values (15.7 mW at 20 °C and 2.7 mW at 110 °C) yet obtained from a blue GaN-based VCSEL, as a result of introducing a long-cavity (10λ) structure and reducing the reflectivity (to 99.1%) of the front cavity mirror. Compared with a 5λ-cavity VCSEL, the thermal resistance was reduced from 1100 to 710 K/W. An analysis of thermal resistance revealed a high internal temperature of 434 K at the rollover point in these devices. This improvement, together with the adjusted reflectivity of the front mirror, led to superior performance, including a high output power of 15.7 mW, a differential efficiency of 31%, and a wall-plug efficiency of 8.9% at 20 °C, as well as a maximum CW operational temperature of 110 °C together with a significant output power of 2.7 mW. These results mark a major step toward establishing high-power GaN-based VCSELs.

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Fig. 4. Temperature dependence of threshold current under CW operation.