Single transverse mode operation of GaN-based vertical-cavity surface-emitting laser with monolithically incorporated curved mirror

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We report single transverse mode operation of a blue GaN-based vertical-cavity surface-emitting laser (GaN-VCSEL) with a monolithically incorporated curved mirror. For a device with a 4 μm current aperture diameter and a curved mirror with a radius of curvature (ROC) of 51 μm, single transverse mode operation was confirmed up to an output power of 3.2 mW under continuous wave operation at 20 °C. For a device with a smaller ROC of 31 μm, multi transverse mode operation was confirmed, indicating that the transverse mode can be controlled by the cavity design of such GaN-VCSELs.

A schematic diagram of a fabricated GaN-VCSEL is depicted in Fig. 1. The fabrication process has been described in detail elsewhere. 20) This suppresses diffraction loss for the applied small current aperture. 18–20)

Another benefit of using a curved mirror is that it allows high-power single transverse mode operation, which is attractive for many application fields, and has already been demonstrated for GaAs-VCSELs. 21–26) For VCSELs, a higher power is generally available with a larger current aperture. However, for standard VCSELs where an index step is applied for lateral optical confinement, to achieve single transverse mode operation, the current aperture diameter is usually scaled down to around 3 μm to prevent higher order transverse modes from being excited, resulting in a limited optical output power of typically around 3 mW for an 850 nm GaAs-VCSELs with oxide aperture current confinement.27)

Using a curved mirror is a better solution because the lateral optical confinement, or the beam spot size of the fundamental transverse mode, can be adjusted to a large current aperture by designing the cavity parameters, including the ROC. 21–26) In addition, using a curved mirror in the GaN-VCSEL structure allows the use of an even longer cavity than that in Ref. 14, which should produce a structure with superior heat dissipation. 28) By the combination of a controllable transverse mode and presumably superior heat dissipation, the proposed structure has the potential to allow high-power single transverse mode operation for GaN-VCSELs. However, single transverse mode operation for even milliwatt power levels has not yet been reported for GaN-VCSELs with curved mirrors, nor have their transverse mode characteristics been reported.

In this report, we present single transverse mode operation with a practical optical output power (>1 mW) for GaN-VCSEL devices with monolithically incorporated curved mirrors. The transverse mode characteristics of the devices are also investigated based on the far-field, near-field, and emission spectra. To verify the controllability of the transverse mode, two devices with different ROCs and current apertures of the same size are fabricated. In addition, a further improvement of the optical output power in the single transverse mode is discussed for the fabrication of a multi transverse mode device with a large current aperture of 8 μm.

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Boron ion implantation was used to form a current aperture. The number of bilayers for the DBR is less than that in the previous report. The epitaxial layers, consisting of n-GaN, three InGaN/GaN quantum wells, and p-GaN, were formed on a c-plane n-GaN substrate by metal organic chemical vapor deposition. An indium tin oxide (ITO) layer and a top-side DBR made of seven Ta$_2$O$_5$/SiO$_2$ bilayers was formed by vacuum deposition over the p-GaN. Boron ion implantation was used to form a current aperture with a diameter from 3 to 8 μm. Metal electrodes (Ti/Pt/Au) were formed on both the ITO and the n-GaN, which was exposed by reactive ion etching, establishing current paths for injecting holes and electrons, respectively. The backside of the wafer was polished, resulting in a wafer thickness of around 20 μm. A curved surface was then formed on the polished back side, the (000-1) plane of GaN, using ball-up resin patterns as sacrificial masks during reactive ion etching of the GaN. The ROC of the curved surface was controlled with a diameter from 3 to 8 μm. Metal electrodes (Ti/Pt/Au) were formed on both the ITO and the n-GaN, which was exposed by reactive ion etching, establishing current paths for injecting holes and electrons, respectively. The backside of the wafer was polished, resulting in a wafer thickness of around 20 μm.

A curved surface was then formed on the polished back side, the (000-1) plane of GaN, using ball-up resin patterns as sacrificial masks during reactive ion etching of the GaN. The ROC of the curved surface was controlled with a diameter from 3 to 8 μm. Metal electrodes (Ti/Pt/Au) were formed on both the ITO and the n-GaN, which was exposed by reactive ion etching, establishing current paths for injecting holes and electrons, respectively. The backside of the wafer was polished, resulting in a wafer thickness of around 20 μm.

Fig. 1. (Color online) Schematic diagram of fabricated GaN-VCSEL with a curved mirror. The white dashed line represents the waveguide established by the curved mirror.

Fig. 2. Emission spectrum measured at current of 1.2 × $I_{th}$ for device with 6 μm current aperture. The multiple peaks indicated by the solid triangles are associated with the longitudinal mode.

Fig. 3(b) shows the dependence of the FWHM for the FFPs on the ROC. The values almost agree with the theoretical line calculated using the following equation:

$$\theta_{FWHM} = \sqrt{2} \ln 2 \frac{\lambda}{\pi \omega_0},$$

where $\omega_0$ is half of the beam waist (at 1/e$^2$) for the fundamental transverse mode formed at the plane mirror for a cavity with a plane and a curved mirror, and is given by the following equation:

$$\omega_0 = \frac{\lambda}{\sqrt{\pi nLR - L^2}},$$

where $R$ is the ROC of the curved mirror.

Figure 4(a) shows emission spectra taken at currents of 1.2 × $I_{th}$ and 1.5 × $I_{th}$ for a device with a 6 μm current aperture and a 51 μm ROC. In this figure, higher order transverse mode peaks (some of which are indicated by red arrows) are also observed between the periodic longitudinal mode peaks. The fundamental transverse mode peak is dominant at a current of 1.2 × $I_{th}$ and the first-order transverse mode peak adjacent to the peak becomes dominant at a current of 1.5 × $I_{th}$. It is also observed that the near-field changes from a circular shape to a doughnut-like shape at around the corresponding current. Figure 4(b) shows emission spectra measured at a current of 1.2 × $I_{th}$ for four devices with the same ROC of 51 μm and different current aperture diameters of 3, 4, 5, and 6 μm. In this figure, numerous peaks associated with higher order transverse modes can be seen for the largest current aperture of 6 μm. They decrease as the size decreases and almost vanish for the 3 μm current aperture where only the peaks associated with the longitudinal mode are observed. This result can be explained by the fact that the
higher order transverse modes have broader electric fields in the radial direction. From the results in Figs. 3 and 4, it is confirmed that the incorporated curved mirror functions effectively in controlling the lateral optical confinement for the fabricated GaN-VCSELs.

Figure 5 shows the measured characteristics of two devices with the same current aperture of 4 μm and different ROCs of 31 μm (device A, left side) and 51 μm (device B, right side). The designed and measured characteristics for these devices are summarized in Table I. For device A, both the emission spectrum and FFP exhibit multiple peaks, indicating multi transverse mode operation from 2 mA, or 2 × Ith. For device B, the FFP exhibits Gaussian-like profiles up to 6 mA, corresponding to 5 × Ith and an optical output power of 3.2 mW. The emission spectrum taken at 6 mA shows a dominant peak with a SMSR of 30 dB at a wavelength of 443.2 nm, indicating fundamental transverse mode operation. The observed difference in the transverse mode between the two devices can be intuitively understood based on the factor 3ω0/φa (listed in Table I), where φa is the current aperture diameter and 3ω0 is a diameter corresponding to 99.7% of the entire area of the Gaussian profile. ω0 is calculated by Eq. (3) with a cavity length of 22 μm for these devices. For device A, 3ω0/φa is calculated to be 0.68, suggesting that some of the higher order transverse modes are not cut off. The value for device B is 0.91, indicating efficient cut off for higher order transverse modes. In the spectrum for device B, the first-order transverse mode still exists, but does not contribute to the lasing for the entire measured range due to a larger modal optical loss than for the fundamental transverse mode. From these results, it can be concluded that single transverse mode operation can be controlled by the ROC for these GaN-VCSELs.

In Fig. 5, it can be seen that device A exhibits a lower threshold current and a higher maximum optical output power than device B. The lower threshold current for device A is considered to be due to the weaker electric field in the radial direction associated with the fundamental transverse mode. This leads to less optical loss at the aperture edge than in device B. Note that lasing occurs in the fundamental transverse mode, and 3ω0/φa is not an optical confinement factor. The smaller value of 3ω0/φa for device A would be expected to reduce its slope efficiency because of inefficient consumption of injected carriers at the aperture edge. However, this applies only to the fundamental transverse mode. Higher-order transverse modes with larger radial electric fields in the radial direction also contribute to lasing in device A, so that the slope efficiency is as high as that for device B. The combination of a comparable slope efficiency and a lower threshold current therefore leads to a higher maximum optical output power for device A.

Figure 6 shows the I–V–L characteristics measured for a device with an 8 μm current aperture and an 82 μm ROC (device C in Table I). The figure also shows the I–V–L characteristics obtained for devices A and B. For device C, a maximum output power of 15.4 mW is obtained, which far
exceeds those for devices A and B, because of the lower operating voltage and thermal resistance owing to the larger current aperture. The device exhibits multi transverse mode operation from 6 mA, or $1.5 \times I_{th}$, (see the FFP shown in the inset in Fig. 6) due to the unoptimized ROC of 82 $\mu$m, and thus a small $3\omega_0/\phi_a$ of 0.54. However, for a much larger ROC of around 0.5 mm, which corresponds to $3\omega_0/\phi_a \approx 0.9$, a stable fundamental transverse mode operation will be obtained, as for device B in Fig. 5. In addition, the wall-plug efficiency calculated for device C reaches 9.2% at an output power of around 10 mW. The efficiency and the maximum output power are comparable with the highest values for GaN-VCSELs reported by Kuramoto et al.\textsuperscript{14).} This supports the prediction that our structure also has superior heat dissipation due to its long cavity. Therefore, we consider that our structure is promising for high-power single transverse mode operation for GaN-VCSELs due to the combination of the controllability of the transverse mode and the long cavity.

In conclusion, we reported single transverse mode operation of a blue GaN-VCSEL with a monolithically incorporated curved mirror at the bottom end of its cavity. For a device with a 4 $\mu$m current aperture and a curved mirror with a 51 $\mu$m ROC, fundamental transverse mode operation was
confirmed up to $5 \times I_{th}$ or an optical output power of $3.2 \text{ mW}$, with a SMSR of 30 dB under CW operation at 20 °C at a wavelength of 443.2 nm, while multi transverse mode operation was confirmed at $2 \times I_{th}$ for a device with a 31 $\mu$m ROC. These results show that the transverse mode can be controlled by the cavity design for GaN-VCSELs with curved mirrors. In addition, higher optical output power of the fundamental transverse mode will be available by further cavity design optimization with an additional advantage of superior heat dissipation derived from a long cavity, which is an inherent structural property for GaN-VCSELs with curved mirrors.

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