Room-temperature continuous-wave operation of green vertical-cavity surface-emitting lasers with a curved mirror fabricated on \{20−21\} semi-polar GaN

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We demonstrate a room-temperature continuous-wave operation of green vertical-cavity surface-emitting laser (VCSEL) with a 20 μm long cavity possessing a dielectric curved mirror formed over a \{20−21\} semi-polar gallium nitride substrate. The emission wavelength and the threshold current were 515 nm and 1.8 mA, respectively. We also confirmed that white light is generated by overlaying three prime colors of light, i.e. red, blue and green, emitted only from VCSEL. © 2020 The Japan Society of Applied Physics

Vertical-cavity surface-emitting lasers (VCSELs) feature small threshold, circular beam, arranging capability, which are superior to LEDs and edge-emitting lasers (EELs). Though many VCSELs have been reported, green emission is still difficult due to thermal blockage at the bottom side mirror placed a-few-micron beneath the InGaN quantum wells (QWs) that suffers from low quality caused by high indium concentration. Originally, GaAs, AlAs and their alloys are exceptionally convenient for use in VCSELs. They have virtually identical lattice constants and relatively large refractive index differences. Laminating flat layers made of these materials creates a highly reflective structure called a distributed Bragg reflector (DBR), providing plane mirrors of up to 99.9% reflectivity. AlAs layers are easily oxidized to produce apertures, i.e. waveguides. Combining such components forms vertical cavities, which enables VCSEL operation. Moreover, all these materials can be thermally and electrically conductive. Thus, electric paths and heat exhausts can be established by placing electrode and heat sinks outside the mirrors. Including an phosphide active layer allows red emission from the cavity.

However, a similar approach does not work for material systems based on GaN, which is used for blue and green light sources in LEDs and EELs. Nitride-based semiconductor DBRs are an important category for bottom side mirrors. There are materials that have lattice constants matching that of GaN, such as AlInN. Thus, bottom mirrors consisting of laminated flat layers made of AlInN and GaN are often used in VCSEL fabrication, exhibiting successful blue and blue-violet emission. However, there are currently no reports on green VCSELs using this approach. It seems to be difficult to achieve high reflectivity, due to the small refractive index difference between these materials in the green region. Instead, dielectric materials such as two types of oxides are used for the mirror fabrication, as these materials can have a bigger difference in their refractive indices in the green region. However, there is a problem. Nichia Corporation has reported a trial of green VCSELs with only pulsed operation for blue-green lasers (>471 nm). Because the oxides have a low thermal conductivity of around 1 WmK−1, the DBRs block heat dissipation out of the cavity. This issue would be serious for an AlInN/GaN DBR, as AlInN has a low thermal conductivity of 4.5 WmK−1, considering that the DBR has thicker laminating due to the smaller refractive index differences in the green region.

One basic approach to mitigate this problem is to extend the cavity length. It has been reported that extending a cavity filled with highly thermal conductive GaN (130 WmK−1) effectively improves the thermal resistance of a device and a cavity longer than about 10 microns is not affected by the bottom mirror’s heat blockage. However, extending a cavity to e.g. 20–50 μm increases the diffraction loss enough to prevent laser operation. Thus, a few microns is the most popular value for the cavity length for GaN-based VCSELs. The present authors recently reported the successful fabrication of blue VCSELs with 20–50 μm cavities by incorporating a curved mirror. The curved surface is fabricated using ballasted resin droplets used as sacrificial masks for a reactive ion etching (RIE) process, which creates efficient waveguides and eliminates diffraction loss and allows the lowest thermal resistance for GaN-based VCSELs due to its length. In this structure, which we consider in the present study, the threshold current is 0.25 mA and the wall plug efficiency (WPE) is 9.5% for blue emission. The authors also pointed out that disturbance in cavity length does not seriously affect it’s laser characteristics as far as the device contain a curved mirror.

Another approach is to incorporate a quantum-dot (QD) based active-region. Because the emission characteristics of QDs are independent of temperature, they are not affected by thermal disturbance. Xiamen University has reported GaN-based VCSELs with QDs allowing emissions across the blue-green to yellow-green region. The authors reported that the structure allowed an incredibly low threshold current density less than 1 kA cm−2. However, the stability of the emission wavelength remains a challenge as it is affected by inconsistencies in QD quality and instabilities in controlling the cavity length, resulting in variation in the emission wavelength (e.g. 507–565 nm). This kind of VCSEL also suffers from filamentation lasing, apparently due to the spatial inhomogeneity of QDs, inhibiting beam formation, which is the essence of laser action.
Another problem, in addition to the thermal properties, is the high threshold current caused by degradation of QWs due to mechanical stress in the InGaN, arising from the high indium concentration. Nichia Corporation reported a drastic increase in threshold current, from 1.5 mA at 451 nm to 12 mA at 471 nm. More specifically, the piezoelectric field induced by strained InGaN QWs causes deterioration of $J_\text{th}$ for green emission. This field is most prominent for the c-orientation, and thus employing a semi-polar or non-polar GaN substrate has shown the most success for green EELs such as {20 − 21}, {20 − 2−1}, or {10 − 10} (23) can reduce the threshold current. (24) {20 − 21}-GaN has shown the most success for green EELs (25–26) as it exhibits several advantages for QWs, such as weak piezoelectric fields, high compositional homogeneity (27) and a high incorporation rate of indium during crystal growth. The latest research shows that this type of EEL can achieve a WPE as high as 17.5% with a maximum output power of 2 W for an emission wavelength of 530 nm. (29) As early as 1997, calculations predicted that the {20 − 21} plane provides sufficient gain for vertical emission. (30) Thus, we can expect that employing {20 − 21}-oriented GaN-substrates will allow the development of green VCSELs.

Accordingly, the present study investigates the feasibility of CW operation of green VCSELs with a curved mirror on the bottom side formed of {20 − 21}-plane GaN. Figure 1(a) shows the device structure used in this study.

The fabrication process was as follows. MOCVD was used to grow four QWs (InGaN/GaN MQWs), a p-GaN layer doped with Mg ($\sim 1 \times 10^{19}$ cm$^{-3}$), a contact layer doped with Mg ($\sim 1 \times 10^{20}$ cm$^{-3}$), and a total thickness of 130 nm, on a (20 − 21) GaN substrate. Two Ti/Pt/Au electrodes were deposited on the contact layer. The thickness of DBRs were controlled so as to its reflectivity peak be 515 nm. A hole was etched next to the aperture, reaching the n-GaN layer. A circular current injection region was electrically connected to the ITO layer and the exposed n-GaN, respectively, forming a current path. A circular current injection region was electrically confined by boron implantation, (31) arranged on a single wafer and designed to have a 4-micron diameter. The aperture was placed in contact with the ITO and Ti/Pt/Au electrodes. The wafer was lapped to a thickness of about 20 μm. Resin disks with diameters of 26 μm were photolithographed on the lapped face of the GaN wafer with (20 − 2−1) orientation. By heating the specimen to 200 °C, the disks were melted into droplets. RIE was used to transfer the surficial shape of the resin droplets onto the GaN substrate by removing them as sacrificial masks, which left a lens-shaped surface on the GaN. An n-side DBR with 14 Ta$_2$O$_5$/SiO$_2$ bilayers was deposited on the curved mirrors. Finally, the device was diced and mounted on a Ø5.6 TO-CAN package without sub mounts in the p-up configuration.

The dimensional characterization of the curved mirror was implemented in multiple ways before the deposition of the DBRs. The cross-sectional dimensions of the curved mirror were measured using confocal laser scanning microscopy (Keyence VK-X1000). The roughness of the top of the curved and plane surfaces formed on the GaN were measured using atomic force microscopy (AFM; Bruker Dimension Icon). As specimens for measurement of the reflectivity spectra of the DBRs, we deposited DBRs with the same structure as that used in the device on BK7 glass plates. The reflectivity spectra of these samples were measured using a spectrophotometer (Hitachi U-4000).

The measurements for the device were conducted with a specimen of a packaged finish, used for tests, I−L and I−L curves, spectral measurements, polarization, far-field pattern and near-field image observations. The current source (ADCMT8230E) was operated in a continuous wave mode. The device was set on a socket with a Peltier cooler (Asahi-data ALP-7033CAP, 25 °C). The optical output of the device was measured by a power meter (ADCMT 6240). The near-field image was observed by a microscope (Nikon LN150A). Emission spectra were measured by a spectrometer (YokogawaAQ6373, resolution = 0.1 nm, sensitivity = HIGH1) via an optical fiber (Thorlabs M43L02 105 μm 0.22 NA). The polarization was observed by monitoring the output power after a polarizer (Thorlabs WP25M-VIS). The far-field pattern was observed by a CCD (Coherent LASER CAM HR). By observing how the beam profile on the CCD expands with the distance between the camera and the device, the emission angle was determined.

The obtained I−L curve [Fig. 2(a)] shows a threshold at 1.8 mA ($J_\text{th} = 14.4$ kA cm$^{-2}$). The WPE was less than 0.1%. The emission spectra [Fig. 2(b)] has a peak at 515.2 nm,
which hops to 517.9 nm across the injection current from 5 to 6 mA. The hopping interval of 2.7 nm corresponds to a cavity length of 18.6 μm, assuming a refractive index of 2.40 and \( dn/d\lambda = -0.00063 \) nm\(^{-1}\). This is consistent with the targeted value for cavity length of ∼20 μm. Thus, these two peaks are thought to be adjacent longitudinal modes. The degree of polarization [Fig. 2(c)] was 0.14 at 1 mA and drastically increased to 0.73, 0.98 and 0.93 at 2, 4 and 8 mA, respectively. The polarization angle is locked to the crystal orientation [−1210], namely the α-direction. Near-field images [Fig. 2(e)] show a circular pattern that shrinks and brightens when the current crosses \( I_{th} \). The far-field pattern [Fig. 2(d)] shows a single peak, which can be fit by a Gaussian curve with full width half maximum of 8.8° and 9.5° for the directions [−1014] and [−1210], respectively. This emission pattern corresponds to a spot size of 2.4–2.6 μm, coinciding with the small spot appearing in the near-field image. All these observations were made under CW
current injection at room temperature. The results presented above indicate laser operation of green VCSELs.

Figures 3(a)–3(c) show the curved surface dimensions and morphology observed by laser scanning confocal microscopy and atomic force microscopy. The figures show a circular and ultra-smooth curved mirror. The morphology of the curved surface of GaN mainly depends on the smoothness of the resin droplets, not on the morphology of the \([20-21]\) GaN surface, resulting in a smooth curved mirror. Moreover, it is notable that the cross section of the curved surface is almost the same in two directions, 41.3 and 42.4 \(\mu\)m for \([−1014]\) and \([−12−10]\), respectively, though the crystal orientation of GaN used for substrate is tilted. The cavity length of 18.6 \(\mu\)m and curved mirrors with such radii form an optical spot of 2.4 \(\mu\)m,\(^{20}\) which corresponds to the obtained value from the far-field pattern profiles. Thus, the curved mirror defines the lateral optical confinement in the cavity.

Combining the present device and existing blue and red devices enables full color light VCSEL sources. Figure 1(a) show pictures of a white circle formed by overlaying red, green and blue beams from VCSELs. This is the first example of a VCSEL-based full color light source, which will have a great impact on the industry. Currently, the displays of smartphones, tablets, laptops, smartwatches and other devices emit light over a wide range, only a small fraction of which is visible. Consequently, these displays waste almost all of their emitted flux. VCSELs, with high directivity and tiny power, can deliver a sufficient amount of visible light without such a dispersal. Retinal scanning displays is an example application of the use of VCSELs.

We will now address the scientific impact of the present results. EELs have flourished recently, employing a wide range of III–V materials including arsenide, phosphide, nitride and their alloys, and being applied to various practical uses in modern society. The key to the success of EELs is the universality of the cavity fabrication process, ridge waveguides formed by RIE connecting two dielectric DBRs formed by vacuum deposition on the edges. This is very similar to the present study, in which the wave guide (curved mirror) is formed by RIE and the mirror is made of dielectric

Fig. 3. (Color online) Results for the dimension and morphology of the curved mirrors. (a) Laser confocal scanning image on a curved surface of GaN. (b) Cross-sectional profile of the surface. Both (a) and (b) show that an ideal parabolic curve is formed over the \([20−2−1]\) side of the GaN without any apparent distortion in its shape. (c) Atomic force microscopy image on the curved surface, showing a smooth surface with a root mean square of 0.45 nm. (d) Reflectivity spectra obtained over a flat portion of the mirrors, where the peak reflectivity reaches almost 100%.
materials. This is very different from the approach used in the past with GaAs-based VCSELs where both the waveguide and mirror were fabricated by epitaxially grown semiconductors. We believe that this new type of cavity has the potential to expand VCSELs to materials other than GaAs, such as GaN and others, and that it will enable wider practical uses of VCSELs across ultraviolet to infra-red deeper than ever.

Competing interests statement
This study is conducted as part of Sony Corporation’s research activity. The authors declare there are no other competing interests.

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