Low threshold continuous-wave lasing of yellow-green InGaN-QD vertical-cavity surface-emitting lasers

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Abstract: Low threshold continuous-wave (CW) lasing of current injected InGaN quantum dot (QD) vertical-cavity surface-emitting lasers (VCSELS) was achieved at room temperature. The VCSEL was fabricated by metal bonding technique on a copper substrate to improve the heat dissipation ability of the device. For the first time, lasing was obtained at yellow-green wavelength of 560.4 nm with a low threshold of 0.61 mA, corresponding to a current density of 0.78 kA/cm². A high degree of polarization of 94% were measured. Despite the operation in the range of “green gap” of GaN-based devices, single longitudinal mode laser emission was clearly achieved due to the high quality of active region based on InGaN QDs and the excellent thermal design of the VCSELS.

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1. Introduction

Gallium nitride (GaN)-based vertical-cavity surface-emitting lasers (VCSELs) have attracted much attention over the past few years due to their potential applications in solid-state lighting, high-density optical data storage, high resolution printing, and biochemical sensing. VCSELs with planar micro-cavity structure offer several distinct advantages over conventional edge-emitting lasers, including lower threshold current, single longitudinal mode operation, high speed modulation, circular beam profiles, wafer-level testing, densely-packed two-dimensional arrays, etc [1]. As efforts have been devoted to this enterprise, lasing of current injected GaN-based VCSELs with different structures from near ultraviolet to green has been reported by several groups by using a mixture of semiconductor and dielectric distributed Bragg reflectors (DBRs) [2–4] or all-dielectric DBRs [5–10]. However, demonstration of GaN-based VCSELs is still suffering from two principal problems. One is the difficulty to obtain high efficiency quantum well (QW) active region because of the high-density dislocations and the strong stain-induced piezoelectric field and the resulting quantum confined Stark effect (QCSE) due to large lattice mismatch between GaN and c-plane sapphire [11, 12]. The large QCSE in InGaN QWs severely limits the internal quantum efficiency and the emission intensity of GaN-based optoelectronic devices, especially for the green and longer wavelength regions (the so called “green gap”) [13]. As a result, devices incorporating InGaN/GaN QWs with high indium content suffer from a serious efficiency drop at high injection level [14]. The other major problem is related to the efficient thermal management for achieving a continuous-wave (CW) output at room temperature (RT). Large self-heating and/or poor heat dissipation under high current density may prevent the device from CW lasing [4, 8]. To overcome these problems, various attempts have been made in the past years. Firstly, the epitaxial structure was grown on a GaN substrate instead of a sapphire substrate to reduce the defect density and ensure good crystal quality of the active layers [4,
6–8, 10, 15]. A weak QCSE thus could simultaneously be obtained in InGaN QWs due to the superior lattice matching on a GaN substrate. Secondly, vertical contact configuration and metal bonding technique were employed to avoid current crowding and improve heat dissipation ability of the devices [5–10, 15]. Despite all these efforts, RT CW lasing in the green region for a GaN-based VCSEL with InGaN/GaN QWs is still very difficult although it has been demonstrated under pulsed operation by Nichia corporation [6].

With the rapid development of the crystal growth technology of III-nitrides, quasi-zero dimensional InGaN quantum dot (QD) structures have been utilized instead of the widely used InGaN QW to obtain low-threshold semiconductor lasers [16]. Generally, the reduced dimensionality of the active region offers several advantages such as smaller effective active volume, stronger carrier localization, higher temperature stability, and smaller radiative carrier lifetime. As to the nitride semiconductors investigated here, it has been shown both theoretically and experimentally that the piezoelectric polarization field is effectively reduced due to strain relaxation process in the InGaN QDs [17, 18], which suppresses the QCSE and enhances the overlap of electron and hole wave functions. Moreover, the QDs inherently contain a much lower density of structural defects in comparison with the QWs, resulting in a high radiation efficiency.

In the present study, RT lasing of yellow-green GaN-based VCSELs was achieved under CW operation, for the first time, by using the InGaN QD structure active regions and a highly thermally conductive copper substrate. The laser emitted with 560.4 nm in the “green gap” spectral range, which is the longest wavelength ever reported for GaN-based VCSELs. The threshold current is as low as 0.61 mA corresponding to a current density of 0.78 kA/cm², accompanied by a setup-resolution limited spectral linewidth of about 0.16 nm and a high degree of polarization of 94%.

2. Device fabrication

The schematic diagram of the fabricated GaN-based VCSEL is shown in Fig. 1(a). The epitaxial layers were grown on a (0001)-oriented sapphire substrate by metal-organic chemical vapor deposition. The active region consisted of two layers of InGaN/GaN QDs. The GaN cap layers on QDs were deposited using a two-step method: a 2-nm-thick low-temperature grown GaN matrix layer was first deposited at the same growth temperature (670°C) of QDs to protect them during subsequent temperature ramping process, then the temperature was ramped to 850°C, and finally, a 8-nm-thick GaN barrier layer was grown. Other detailed growth procedures are described in our previous work [19]. The average indium content of the QDs is about 27%. Atomic force microscope (AFM) scans indicate a dot density of \( \sim 1.5 \times 10^{10} \text{ cm}^{-2} \). Cross-section Z-contrast scanning transmission electron microscopy (STEM) shows that the diameters of the QDs range from 20 to 60 nm, while the average height of QDs is about 2.5 nm. The epitaxial structure was processed as described in the following to fabricate current-injection VCSELs. Firstly, a 10-μm-diameter current aperture was formed by patterning a SiO₂ layer deposited on p-type GaN. Then, a 30-nm ITO layer was deposited as a p-type ohmic contact and current spreading layer, followed by an electrode (Cr 20 nm/Au 200 nm) around the current aperture. To minimize the absorption loss of ITO layer and increase the coupling of photons and carriers, a phase-shift adjustment TiO₂ layer was then deposited on the ITO layer to keep the ITO layer at a node and the QDs active region at an antinode of the electric standing wave. A 12.5-pair TiO₂/SiO₂ DBR was formed as the backside mirror. Subsequently, the sample was bonded upside down to a highly conductive copper substrate by metal bonding. The bonding process was the same as our previous report [20]. Next, the sapphire substrate was removed from the wafer by using a laser lift-off process and the n-type GaN was thinned and polished through inductively coupled plasma (ICP) etching and chemical mechanical polishing (CMP) techniques. Finally, an n-type contact was formed and a top 11.5-pair TiO₂/SiO₂ DBR was deposited. Figure 1(b) shows the picture of the VCSEL array and an enlarged optical microscopy image of the
device with a chip size of 60 μm × 120 μm. The emission light of the VCSEL was collected using a microscope with a 100 × objective and fed into a spectrometer system with a cooled charge-coupled device (CCD) to record the emission spectrum.

3. Experimental results and discussion

Figure 2(a) shows the photoluminescence (PL) spectrum of the InGaN QD sample at 300 K, with an emission peak of ~524 nm. The wide spectrum of the spontaneous emission modulated by the self-formed Fabry-Pérot cavity with mirrors of sapphire/GaN interface and GaN/air interface, is most probably due to inhomogeneity in QD size and alloy composition. The TiO2/SiO2 dielectric DBRs exhibit a broad stopband width of about 150 nm, with peak reflectivities of 99.5% and 99.8% centered at about 525 nm for the top and back sides, respectively. Due to the inhomogeneous broadening of the spontaneous emission and the broadband nature of the DBR stop band, lasing behavior was achieved at yellow-green wavelength of 560.4 nm under CW operation as the first time for the GaN-based VCSELs. Figure 2(b) shows the current-light output and current-voltage characteristics of the yellow-green VCSELs. A clear lasing transition from spontaneous emission to stimulated emission can be observed. The threshold current and threshold voltage are 0.61 mA and 6.7 V, respectively, and the threshold current density is estimated to be 0.78 kA/cm² by assuming the current is uniformly injected within the aperture. Such a low threshold is attributed to the high reflectivities of the DBR mirrors, the strong localization effect and the negligible QCSE in InGaN QDs, and a good coupling between QDs region and the electric field of the lasing mode. It should be noted that the low threshold lasing may benefit from filamentation effect too, because of the inhomogeneous distribution of refractive index caused by both In contents and the higher efficiency of carrier capture of QDs than the surrounding material [21].
Figure 3(a) shows the emission spectra of the investigated VCSEL for various injection currents at 300 K. A single-longitudinal mode lasing behavior was observed at a wavelength of 560.4 nm, with a setup-resolution limited spectral linewidth of approximately 0.16 nm. The spectral longitudinal mode spacing between the adjacent cavity modes is about 24 nm, corresponding to a cavity length of 2.6 μm. It is clearly revealed that the intensity of the lasing peak increased dramatically above the threshold current. The dashed red arrow in Fig. 3(a) indicates the wavelength of green VCSEL reported by Nichia corporation under pulsed current operation. Figure 3(b) shows the evolution of the light emission linewidth with increasing the current. The laser emission spectral linewidth reduces rapidly with the injection current above the threshold and approaches the spectral resolution limit of 0.16 nm at the injection current of 2.2 Iₜh. Figure 3(c) depicts the polarization characteristics of the VCSEL. The degree of the polarization, given by \((L_{\text{max}} - L_{\text{min}})/L_{\text{max}} + L_{\text{min}})\), where \(L_{\text{max}}\) and \(L_{\text{min}}\) are respectively the maximum and minimum relative light intensities, was measured to be 94% under CW operation at injection current of 1.96 Iₜh, corresponding to a high orthogonal polarization suppression radio of 30 dB.

By using a high quality active region based on InGaN QDs, we successfully demonstrate the yellow-green GaN-based VCSELs in the “green gap” spectral range. The “green gap” indicates a severe efficiency drop of green-yellow emitters in comparison with blue and red ones. As mentioned above, both degraded material quality and increased spatial separation of electron and hole wave functions induced by the stronger QCSE in c-plane InGaN/GaN QWs...
would reduce the emission efficiency of the devices with increasing indium content. The latest research reveals that the QCSE in InGaN QWs with high indium content gives the most important contribution to the green gap [14]. Nevertheless, for the InGaN QD sample used here, the excitation power dependent PL spectra exhibit a slight blueshift of the PL peak position together with the broadening of spectra linewidth at the shorter wavelength side at a temperature of 5 K, as shown in Fig. 4(a). Note that if the QCSE plays a role, as the excitation power increases, the screening effect of the QCSE will become stronger, then the PL spectra will shift to shorter wavelengths (blue shift) for both sides of short and long wavelengths [22]. However, no identifiable blue shift of the PL spectra in Fig. 4(a) could be observed at the longer wavelength side, indicating a weak or negligible QCSE in the QD sample. Consequently, the blue shift of the whole PL spectra at the shorter wavelength side and the
broadening of the spectra linewidth are forcibly ascribe to the well-known band-filling effect but not the QCSE. Besides, the temperature dependent PL experiment in our recent report shows strong localization effect and induced high radiation efficiency of the InGaN QDs [23]. Moreover, our calculation shown in Fig. 4(b) manifests a good coupling between QDs region and the electric field for the cavity-mode at 560.4 nm. Consequently, a large gain enhancement factor, given by

$$\Gamma_r = \left( L/d_a \right) \int_{0}^{L} |E(z)|^2 dz \int_{0}^{L} |E(z)|^2 dz,$$

where $L$, $d_a$, $E(z)$ are respectively the cavity length, thickness of active region and electric field distribution, can be expected for the 560.4 nm cavity-mode due to the good overlap of the QDs region and the antinode position of the electric field. All these factors contribute to the laser emission at such a yellow-green wavelength.

![Fig. 4. (a) Excitation power dependence of PL spectra. (b) Calculated electric field distribution for the 560.4 nm cavity-mode of the InGaN QD VCSEL.](image)

4. Conclusion

In summary, we have demonstrated the CW RT operation of an electrically injected GaN-based VCSEL in the “green gap” range for the first time. By using a high quality InGaN QD active region and metal bonding technique, lasing behavior was achieved with a low threshold current density of 0.78 kA/cm$^2$ at 560.4 nm in yellow-green wavelength, which is the longest wavelength ever reported for GaN-based VCSELs. Moreover, a high degree of the polarization was measured to be 94%. The calculation shows a good coupling between the QDs region and the electric field of the lasing mode. The strong localization and the negligible QCSE of the QDs, as well as the good coupling between the QDs region and the
electric field, are believed to work together in obtaining a high radiation efficiency and the subsequent lasing actions in the “green gap”.

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