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InGaN-Based Orange-Red Resonant Cavity Light-Emitting Diodes

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***Abstract*—InGaN-based orange-red resonant cavity light-emitting diodes (RCLEDs), were fabricated by using an AlN current-confinement aperture and double dielectric distributed Bragg reflectors (DBRs). For realizing the structure of device, a substrate transfer technique was employed in process of fabrication. The device exhibited optical resonant effect, a high Q factor (~3010), and a narrow emission linewidth (FMHW ~0.2 nm), indicating low optical loss in the resonant cavity. Additionally, due to the three-dimensional (3D) optical confinement effect, the discrete modes of red emission were clearly observed in the far field via an angular resolved measurement system. And then, the energies of the photon states of a red RCLED consists generally with the simulation results based on a circular waveguide model. The saturated emission intensity of the orange-red RCLED was proportional to the area of current injection. This work demonstrated the feasibility of InGaN-based electrically injected orange-red RCLEDs that are useful for the development of displays and communication systems.**

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***Index Terms*—InGaN quantum well, dual dielectric DBR, 3D optical confinement effect**

I. Introduction

THE development of displays and communication systems has greatly increased the demand for light emission devices. As one of three primary colors, red is an indispensable part of white light and RGB displays [1-5]. There are a few approaches for obtaining red emission. In some cases, blue and ultraviolet light have been used as pumping light sources to excite red-emitting quantum dots and phosphor[6, 7]. However, blue and ultraviolet light are unhealthy for the eyes and skin, which is a growing concern. Semiconductor solid-state devices that can directly emit red light have also drawn much attention worldwide. For red light emission, the aluminum indium gallium phosphide (AlInGaP) system is generally preferred [8-10]. Currently, AlInGaP-based deformable and semitransparent displays and vertical-cavity surface-emitting lasers (VCSELs) have been fabricated[9, 11]. However, due to their inherent narrow energy gap, the applicable wavelength of the devices is significantly limited. Compared to AlInGaP material, light emitted by InGaN/GaN semiconductors can cover the entire visible light range[12-17] [18], Thus, blue, green, and red can be integrated into one chip with the same material system. In 2008, utilizing a selective area growth method, a white light-emitting diode (LED) was fabricated with laterally distributed blue and green InGaN/GaN multiple quantum wells (MQWs). In the electroluminescence (EL) spectra, blue light (447 nm) and green light (514 nm) could both be observed[19]. To improve display resolution and for full-color emission, single InGaN nanowires of various sizes on the same substrate were fabricated using the same method, which emitted blue, green, orange, and red light [20]. Therefore, as red emission devices, InGaN is a promising candidate.

The Fabry Perot (FP) planar cavity is a significant element in optical devices and is generally composed of dual distributed Bragg reflectors (DBRs). Inaba et al. demonstrated that dual DBRs can shorten the lifetime of Eu-related luminescence, improve the directionality of light output, and enhance the output power by formation of GaN:Eu,O-based RCLEDs [21]. Besides, Oh et al. reported that when the reflectivity of the DBRs was increased, the linewidth narrowed. Narrow linewidth and good directionality can improve modulation speed and the rate of data transmission in free space[22].

Therefore, compared to commercial LEDs, RCLED emissions possessed unique properties, such as narrower linewidth, brighter beam, higher color purity, and better directivity, resulting from the resonant cavity effect. In our previous works, we realized blue-green VCSELs, green resonant cavity light-emitting diodes (RCLEDs) with a high Q factor (~6000) [23-26]. At present, GaN:Eu,O and AlInGaP-based red RCLEDs have been reported [9, 21, 27]. However, electrically injected red InGaN-based RCLEDs have not been fabricated until now because some critical difficulties. First, InGaN quantum wells with high indium (In) concentration can hardly be grown by metal–organic chemical vapor deposition (MOCVD), owing to the large lattice mismatch. Additionally, because of insufficient surface migration at lower temperatures, a mass of dislocation and tremendous strain were introduced, resulting in reduced crystalline quality [12, 15, 17, 28-30]. Therefore, the production of high-quality InGaN-based red emission devices is still a difficult challenge.

In this work, InGaN-based orange-red RCLED with dual-dielectric DBR structure under low injection current was fabricated for the first time by using substrate transfer technique. A high Q factor of about 3010 and a minimum emission linewidth of 0.20 nm were realized at 602 nm. In addition, the discrete far-field modes of emission were clearly observed by an angular resolved measurement system, which consists well with the simulation results based on a circular waveguide model. Finally, the light output power of orange-red RCLED with different diameters of emission aperture was found to increase with injection current.

Figure 1(a) shows the structure of the epitaxial wafer. The epitaxial wafers were grown on a (0001) c-plane patterned sapphire substrate via MOCVD. To improve the quality of red double quantum wells (DQWs), a blue single quantum well (SQW) was first grown, and relevant details have been previously reported [12, 29, 31] Figure 1(b) shows a schematic cross-sectional view of an orange-red RCLED. The structure of the red RCLED consisted of a copper substrate, bottom and top TiO_2/SiO_2 DBRs, indium tin oxide (ITO), an AlN lateral confinement layer, an InGaN epitaxial wafer, and a Cr/Au n-electrode. The AlN layer not only conducted a large amount of heat but also confined both electrons and photons[23, 32].

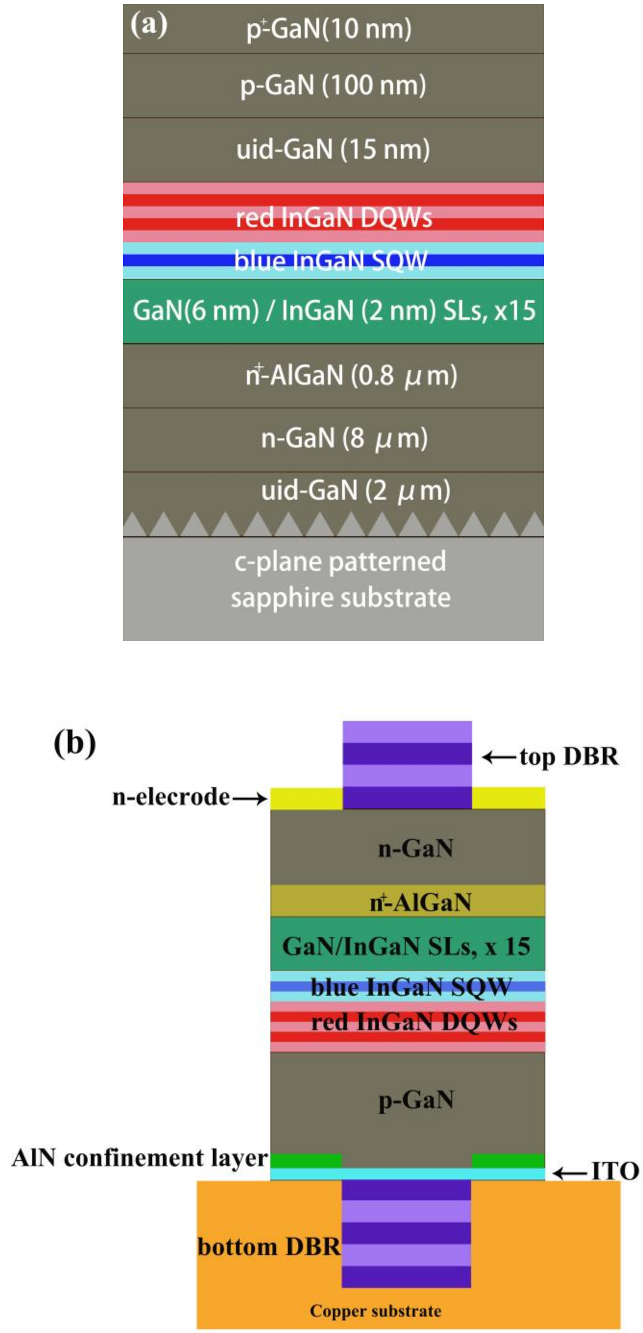

Fig. 1. (a) Schematic structure of the epitaxial wafer. (b) Cross-sectional schematic of InGaN-based orange-red RCLEDs.

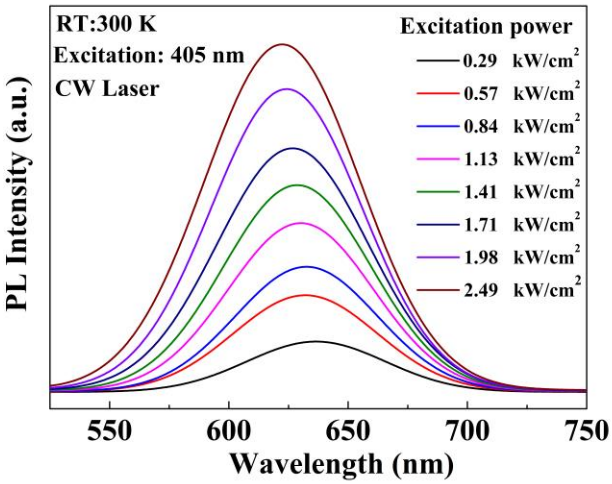

Fig. 2. PL spectra of the epitaxial wafer with varying excitation power at room temperature.

We first measured the room-temperature (RT) photoluminescence (PL) spectra of the epitaxial wafer with varying excitation power and the results are shown in Fig 2. The PL measurements were performed using a 405 nm continuous wavelength laser. The spontaneous emission is centered at around 630 nm. The slight blue shift with increasing excitation power was attributed to the screening of the quantum-confined Stark effect (QCSE) [12, 28, 33].

The same process of fabrication was reported in our previous works [23-25]. Firstly, a mesa with a step height of ~30 nm was fabricated on a surface of p-GaN via lithography process and inductively coupled plasma (ICP) etching. And then, the other area was filled by a 30 nm thick AlN film via magnetron sputtering. The AlN film acted as a current confinement layer. The ITO was deposited on the wafer surface to improve current spreading. Following, the bottom DBR was deposited on p-GaN by electron beam evaporation. For realizing dual DBR, wafer transfer was carried out by electroplating copper supporting plate and laser lift-off (LLO). Since high surface roughness can enhance optical scattering loss, chemical mechanical polishing is usually needed to obtain a flat n-GaN surface after LLO. At last, devices were separated by ICP etching, and Cr/Au negative electrode and top DBR were deposited.

Dual dielectric DBR structure was designed to form a resonant cavity. The bottom DBRs consisted of 12 pairs of TiO_2 and SiO_2 layers. The top DBR consists of 8 pairs of TiO_2 and SiO_2 layers. Fig. 3(a) shows the reflection spectra of the top and bottom DBRs. The reflectivity of the top and bottom DBRs (99.9% and 99.7%, respectively) can remarkably influence the resonant effect and FWHM. In addition, the reflectivity was higher than that of the epitaxial nitride DBR reported (~90%) [34] [35]. The broad stopband of the DBRs (137 nm and 100 nm, respectively) can cover all the EL spectra of red RCLED, as shown in Figure 3(b). Since the electrical pumping has a higher excitation density, which caused serious screening of the QCSE effect, the center of the stopband is designed at around 600 nm. Additionally, a 30 nm thick patterned AlN lateral confinement layer was inserted between ITO and p-GaN. The AlN aperture works for both current confinement and optical confinement, due to its insulating nature and lower refractive index compared with GaN. In addition, AlN can exhaust a large amount of heat in operation [23, 32].

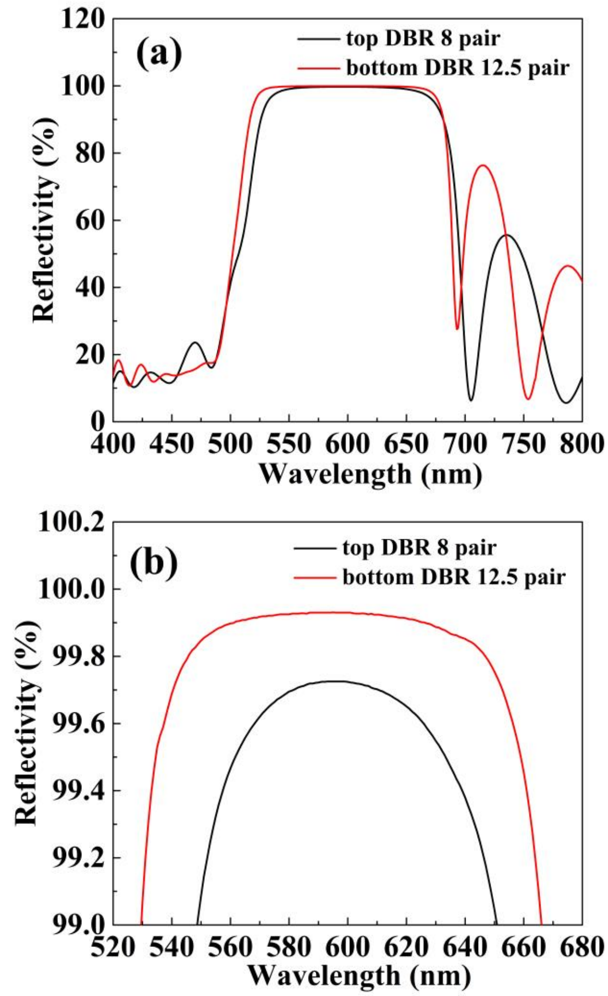

Fig. 3. (a) Reflection spectra of the top and bottom DBRs of the red RCLED from 400-800 nm. (b) Stopband of the top and bottom DBRs.

II. RESULTS

Figure 4 offers the normalized EL spectra of the orange-red RCLED under a 0.03 mA current injection at room temperature. Resonant cavity effect led to four main longitudinal modes locating at 562, 581, 602, and 621 nm. The separation of adjacent fundamental modes was about 20 nm, and the length of the resonant cavity was estimated to be 3.4 μm. The long cavity length contributed to the narrow FWHM and high Q factor [25]. Inset is the photograph of an orange-red RCLED in operation. A bright orange-red emission spot located in the center of the aperture, indicating that the current and photons were confined in the AlN lateral confinement aperture. The weak edge emission originated from the waveguide effect of the structure.

Furthermore, to fully clarify the characteristics of the modes, high-resolution EL spectra measurements were carried out using a 2400 L/mm grating (Figure 5(a)). On the one hand, the fundamental mode at 602 nm exhibited the strongest intensity, much stronger than other higher-order lateral modes. On the other hand, in this work, red emission is focused. Compared to 602 nm, 581 nm is close to yellow emission. Therefore, despite the 581 nm having the same intensity, 602 nm was chosen for the analysis. The intensity distribution obeys the well-known Fresnel model in that the diffraction loss of the fundamental mode is lower than those of other higher-order lateral confined modes. And, a comb of modes results from the lateral confinement. In addition, to evaluate the FWHM and the Q factor of all modes, high-resolution EL spectra were fitted by Lorentzian profiles (Figure 5(b)). As the wavelength decreased, the FWHM showed a rise in volatility, while the Q factor of the modes showed decreased volatility. The fundamental mode exhibited the narrowest FWHM of 0.2 nm, and the highest Q factor was calculated by $\lambda/\Delta\lambda$ to be about 3010. The Q value was much larger than those of AlGaInP-based (Q~45) and GaN:Eu, O-based (Q~84) red RCLEDs [9] [21]. The high Q factor signified a low loss of optical field in the resonant cavity. These outstanding results were due mainly two factors: the enhanced the resonance effect due to long cavity and high reflectivity DBRs; and the successful confinement of both injected current and optical field of red emission.

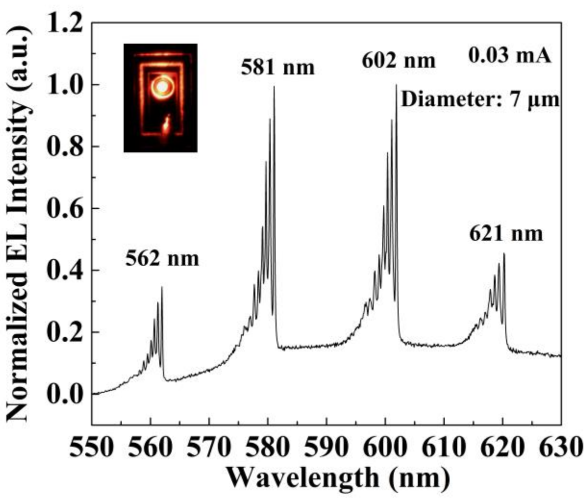

Fig. 4. Normalized EL spectrum of orange-red RCLED, with a current injection of 0.03 mA (current density 77.9 A/cm^2) at room temperature. Inset is a photograph of the red RCLED acquired during EL measurement.

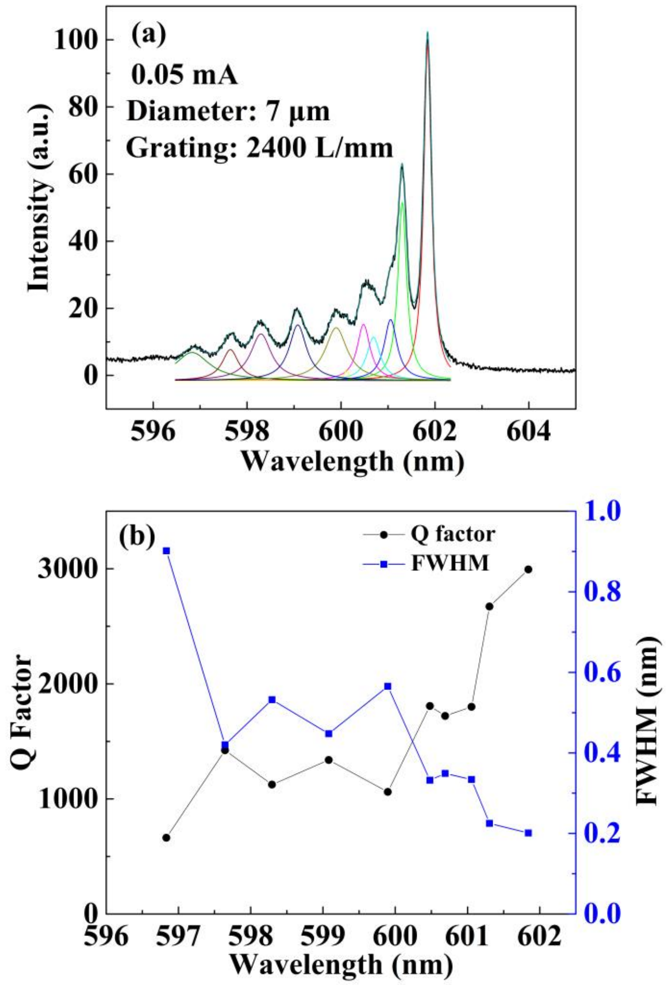

Fig. 5. (a) High-resolution EL spectrum of orange-red RCLED, with a current injection of 0.05 mA (current density 129.9 A/cm^2) at room temperature and curves fitted by Lorentzian profiles. (b) Q values and FWHMs of different modes in (a).

Furthermore, we investigated the far-field modes of 602 nm. The far-field image of the emission modes from a device with a 7 μm AlN aperture was obtained via a lens system that coupled the device emission into a spectrometer with a 256 × 1024 pixel charged-couple device (CCD) image sensor. In this process, the Fourier transform produced by a microscope objective (numerical aperture: 0.3) was projected onto the monochromator. The distribution of the 3D confined optical states in the momentum space was also studied through angle-resolved measurements and is shown in Figure 6(a). The data plot of the far-field modes formed a parabola, and the dispersion of the optical states in k space splits into a series of discrete modes at different energies. The lowest point (E_0, ~2.059 eV) is the energy of unconfined optical state. In addition, with higher energies, their intensities become weaken. This may be due to the varying number of emitting photons in each mode as a result of the different mode volumes [36]. Distribution of the optical states in k space consists well with the high-resolution EL spectrum in Fig.5(a). The fundamental mode in fig.5(a) corresponds to the brightest data spot in Fig.6 (a). The discrete modes showed a symbol indicative of the 3D confinement effect composed of the AlN aperture confined

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layer and DBRs [36, 37]. Data of the far-field modes are useful for understanding the optical characteristics of orange-red RCLEDs and selecting a specific mode.

In the following, we estimate the energies of the photon states using a circular waveguide model. Assuming an ideal perfectly reflecting sidewalls, the energies are written by: [38]

$$Ec(n_\gamma, n_\varphi) = \sqrt{E_0^2 + \frac{\hbar^2 c^2}{n_c^2}\frac{x_{n_\gamma,n_\varphi}^2}{R^2}} \quad (1)$$

where $x(n_\Upsilon\ n_\varphi)$ is the n_Υth zero of the n_φth order Bessel function $Jn_\varphi(x)$, R is the diameter of the waveguide. The calculated results are presented in Figure 6(b). The six lowest states (n_Υ, n_φ) were (1,0), (1,1), (1,2), (2,0), (2,1), and (2,2). Lines in Figure 6 (b) are calculated energies for different modes as a function of aperture diameter (waveguide diameter). It is clear that as the AlN confined aperture diameter is increased, the energy separation between adjacent modes and mode energies continue to decrease. Some experimental data symbols in Figure 6 (b) matched imprecisely with the calculation due to possible imperfections of the model, such as uneven refractive index and slight absorption.

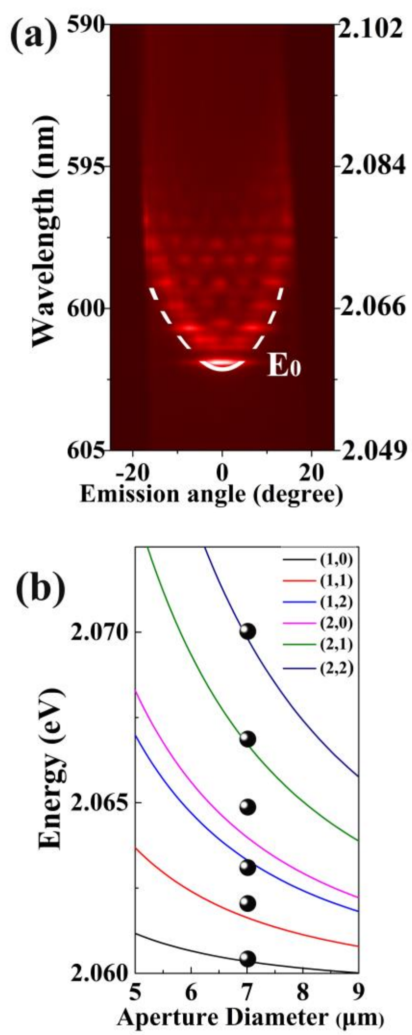

Fig. 6. (a) Emission spectrum of a single device with a 7 μm AlN aperture diameter and a current injection of 0.03 mA at room temperature. (b) Energies of the photon states of a RCLED as a function of diameter. Symbols denote the experimental data, and lines are the results of numerical calculations as described in the text.

Figure 7 presents the I-V curve of the orange-red RCLED. It is seen that the forward turn on voltage of the devices is around 5.7 V. Figure 8 (a) shows the EL integrated intensity of the orange-red emission from 590 to 700 nm. It is noted that with increasing injection current, the strongest emitting cavity mode exhibits large blue-shift. For accuracy, the integration was done with a wider range in order to include a few cavity modes in the red region. With increasing injection current, the intensity immediately increased and then tended to saturate. This can be explained by the following: at lower currents, the intensity is determined by the rapid increase of the injection current in the aperture; while at higher currents, the emission is limited by the number of emission centers (high In-content clusters or quasi-QDs) [33] in the aperture. Figure 8 (b) shows the saturation intensity as a function of aperture area. The almost linear relationship means that the number of emission centers increases in proportion to the area of the AlN aperture. In short, under a low injection current when the number of carriers is less than the number of quasi-QDs, the output power is determined by the injection carrier; whereas under a high injection current when the number of carriers is sufficient, the output power is limited by the number of quasi-QDs.

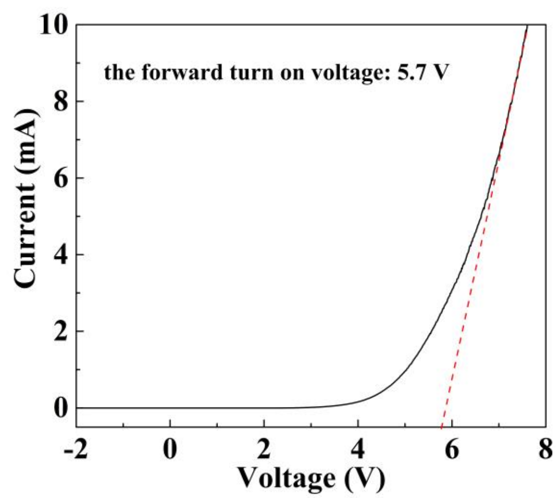

Fig. 7. The I-V curve of the orange-red RCLEDs

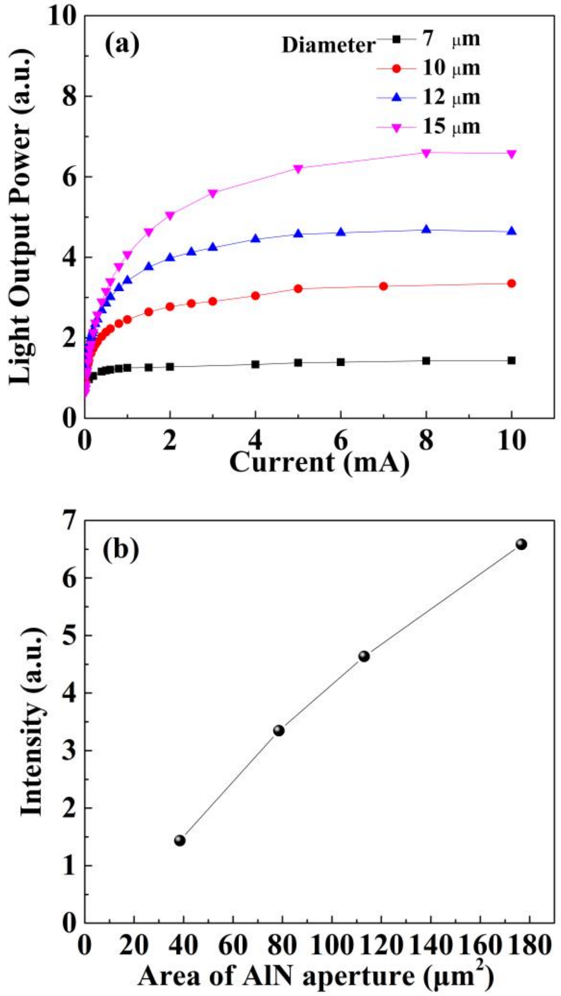

Fig. 8. (a) EL peak intensity at different currents with different aperture diameters. (b) Saturation intensity (at 10 mA) as a function of aperture area.

III. CONCLUSION

In summary, we demonstrated a novel electrically injected InGaN-based orange-red RCLED, with a maximum Q value of 3010 and a minimum FWHM of 0.20 nm. The good performances were realized because of low-loss optical confinement. Its outstanding properties are beneficial for use in displays and communication systems. Furthermore, discrete modes in the far field were clearly observed due to the 3D confined structure composed of AlN confinement aperture and dual DBRs. The saturated emission intensity was found to be proportional to the aperture area, which was explained by the emission centers involved. This work presented findings fundamental for the future optimization of InGaN-based red RCLEDs.

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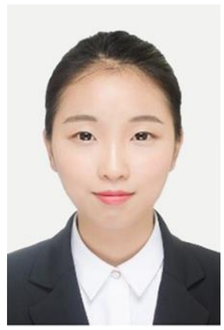

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