Blue resonant-cavity light-emitting diode with half milliwatt output power

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ABSTRACT

GaN-based resonant-cavity light-emitting diode (RCLED) has a circular output beam with superior directionality than conventional LED and has power scalability by using two-dimensional-array layout. In this work, blue RCLEDs with a top reflector of approximately 50% reflectance were fabricated and characterized. An output power of more than 0.5 mW per diode was achieved before packaging under room-temperature continuous-wave (CW) operation. The full width at half maximum (FWHM) of the emission spectrum was approximately 3.5 and 4.5 nm for 10- and 20-μm-diameter devices, respectively. And the peak wavelength as well as the FWHM remained stable at various currents and temperatures.

Keywords: Resonant-cavity light-emitting diode, RCLED

1. INTRODUCTION

Compared to LEDs, RCLEDs have several advantages including narrow spectral widths, stable peak wavelengths at various injection currents, superior directionality, high extraction efficiency, and high output-coupling efficiency due to relatively coherent light output [1]. GaN-based RCLEDs have several potential applications such as high-brightness speckle-free illumination, display, visible light communication, and medical aesthetics. Numerous GaN-based RCLEDs have been reported. Studies emphasized cavity design and/or epitaxial distributed Bragg reflector (DBR) growth [2-6], demonstrated processing techniques [7-9], and reported a new emission wavelength of 390nm [10]. Recently we successfully fabricated RCLEDs featuring a Si-diffusion-defined confinement structure [11]. By using selective Si diffusion, a 3D current confinement structure was produced while keeping a planar top surface for dielectric reflector deposition. However, the output power was quite low due to very high reflectance of the top reflector. In this study, the reflectance of the top reflector was reduced from 99% to approximately 50%, and the peak wavelength of the GaN material was changed from 406 nm to 428 nm. As high as 0.53 mW CW power was obtained under on-wafer probe testing at room temperature.

2. DEVICE STRUCTURE AND FABRICATION

2.1 Epitaxial structure

A schematic diagram of the Si-diffusion-defined RCLED is shown in Fig. 1. A two-inch GaN wafer was grown on a c-plane sapphire substrate by using metal-organic chemical vapor deposition. The epitaxial structure consisted of 25 pairs of AlN/GaN DBRs, 880-nm n-GaN, 10 pairs of InGaN/GaN multiple quantum wells (MQW), a 25-nm-thick p-AlGaN electron blocking layer, 100-nm p-GaN, and 4-nm p-InGaN. The nominal cavity length between the AlN/GaN DBR and the wafer surface was designed to be 7λ, where λ is the effective wavelength in GaN. The maximum reflectance and stopband width at 90% reflectance of the AlN/GaN DBR were measured to be 95% and 16 nm, respectively.

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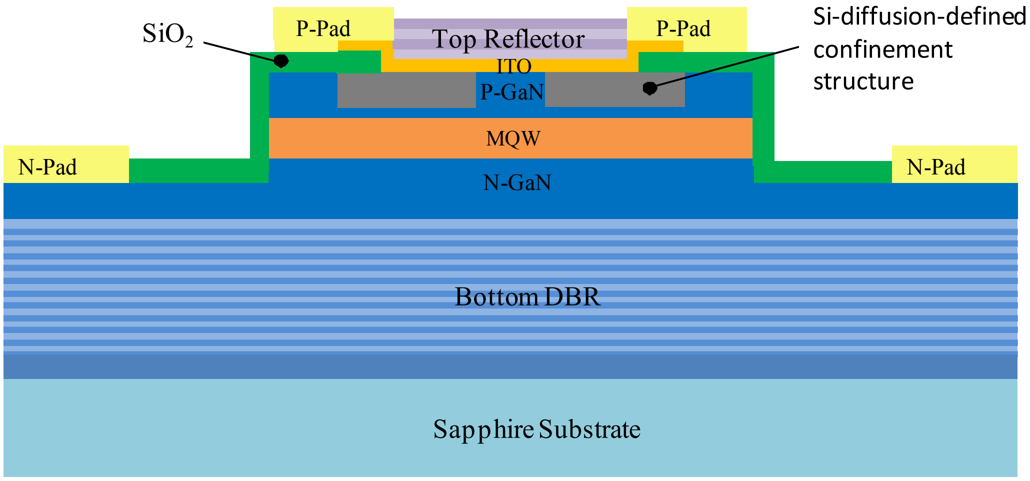


Figure 1. Schematic diagram of the Si-diffusion-defined RCLED, where DBR, ITO, MQW represent distributed Bragg reflector, indium tin oxide and multiple quantum wells, respectively.

2.2 Device fabrication

The devices were processed similarly as described in reference [11] except a 2-pair TiO_2/SiO_2 dielectric reflector was coated on top of the ITO layer using an e-gun evaporation system. The maximum reflectance of the reflector was 50% and the wavelength range having a reflectance between 45% and 50% was from 418 to 460 nm. Fig. 2 shows the reflectance spectra of the top reflector and the bottom DBR measured from a monitoring sample and from the same epitaxial wafer, respectively. For comparison, one column of diodes was protected from the Si diffusion process, and another column was protected from the top reflector deposition. Charge-coupled-device (CCD) imaging was performed before p-metal deposition to record the light distribution when no metal blocking was applied. As shown in Fig. 3, the p-contact probe was placed on the edge of the ITO pad at a constant current of 2 mA and at room temperature; the reference diode that was not subjected to diffusion exhibited a blurred spot with a size corresponding to the size of the ITO pad, which was 30 μm in diameter, whereas the diodes subjected to diffusion exhibited bright, round spots with sizes related to their diffusion-defined aperture sizes.

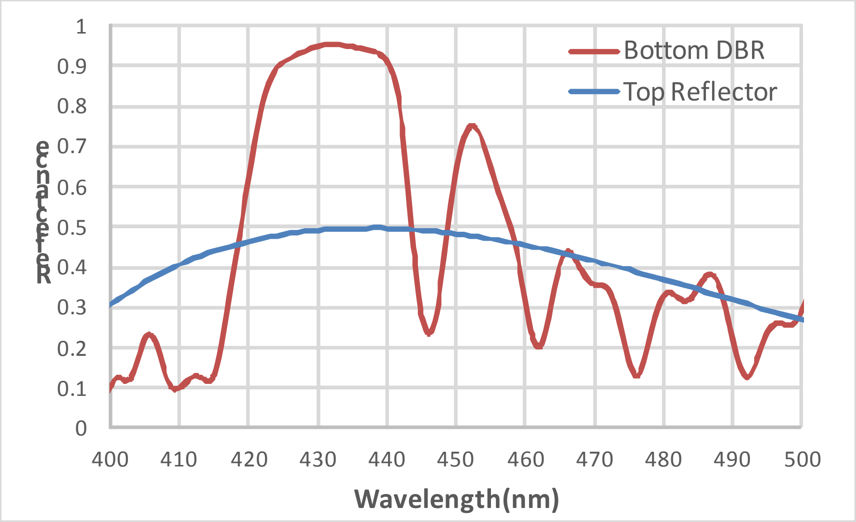


Figure 2. Measured reflectance spectra of the top reflector and the bottom DBR

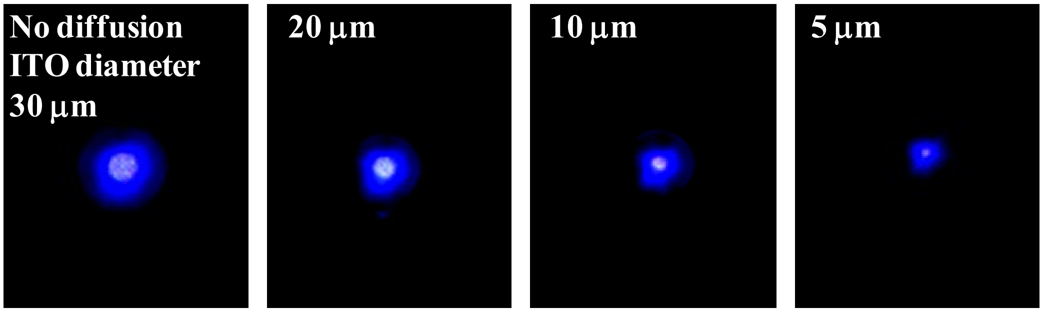


Figure 3. CCD top-view images of devices of various aperture sizes (from left to right): no-diffusion device having an ITO-defined emitting area of 30 μm in diameter, 20-μm-diameter diffusion-defined device, 10-μm-diameter diffusion-defined device, and 5-μm-diameter diffusion-defined device.

3. EXPERIMENTAL RESULTS

Emission spectra of devices at various current injection levels with and without the top reflector were measured as shown in Fig. 4 using a 0.1-nm-resolution optical spectrum analyzer (OSA). The analyzer's fiber was placed at a normal direction to the wafer plane. The collection area was one degree at a subtended angle or 2.39×10^{-4} steradian at a solid angle. With the top reflector, the resonant cavity modes became prominent; the FWHM significantly decreased from 20 to 4.5 nm for 20-μm-diameter devices (3.5 nm for 10-μm-diameter devices due to fewer transverse modes), and the peak wavelength remained stable at various currents. Two longitudinal modes resonated within the bottom DBR stopband with a mode spacing of approximately 13.1 nm. The emission spectra of 10-μm-diameter RCLED at various currents up to a current density of 12.7 kA/cm^2 are shown in Fig. 5; the peak wavelength shift was -0.05 nm/mA in a current range of 4-10 mA. Moreover, Fig. 6(a) and (b) show the emission spectra at various ambient temperatures under on-wafer junction-side-up testing and at a fixed current of 10 mA and 5 mA for 20- and 10-μm-diameter devices, respectively, corresponding to current densities of 3.18 and 6.37 kA/cm^2. The output intensity dropped significantly when the temperature was increased up to 333 K resulted from inefficient heat dissipation; however, the peak wavelength remained stable at 428.1 ± 0.2 nm and 427.7 ± 0.5 nm for 20- and 10-μm-diameter devices, respectively. The peak wavelength shift per degree in temperature increase was less than 0.03nm/°C. Fig. 7 shows the L-I-V curve of 20-μm-diameter RCLED at room temperature; a maximum power of 0.53 mW CW was obtained at 25.2 mA before thermal rollover. Higher output power is expected when packaged. RCLEDs with 10-μm-diameter aperture exhibited more serious thermal rollover problem due to higher current density. In addition, Figure 8(a) and (b) show the far-field patterns of 10-μm-diameter LED and RCLED, respectively, measured by an angle-resolved electroluminescence measurement system. In comparison, the RCLED has a smaller half-power angle of approximately 45° because the resonant cavity effect increased the directionality of its light waves, thereby increasing the extraction efficiency. RCLED with 20-μm-diameter aperture also has a half-power angle of approximately 45°.

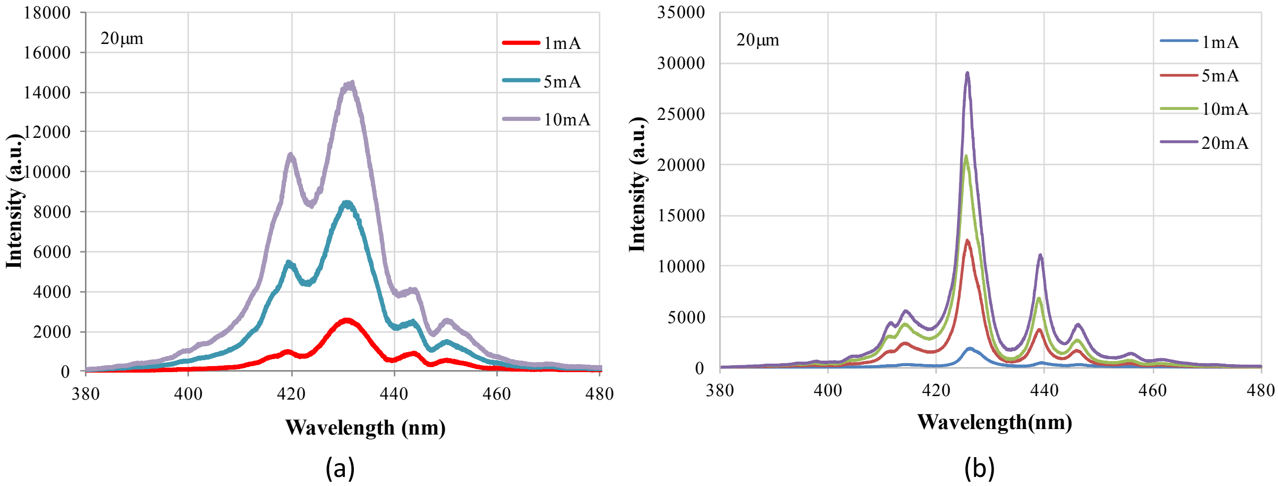


Figure 4. Emission spectra of 20-µm-diameter devices at various current levels (a) without (b) with the top reflector

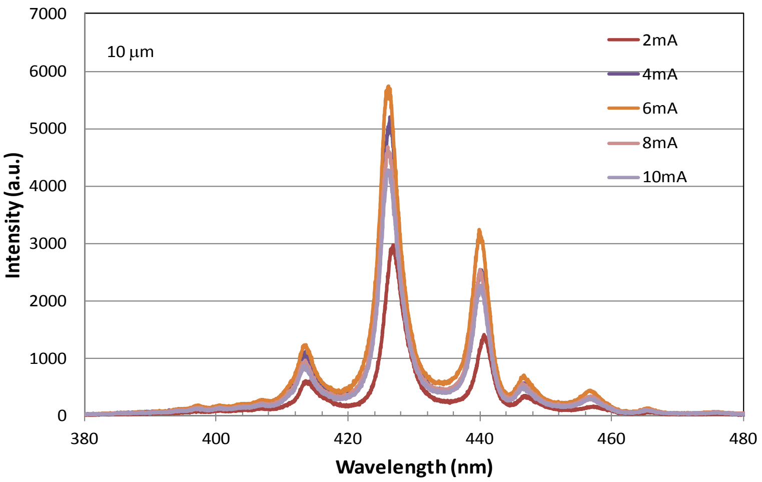
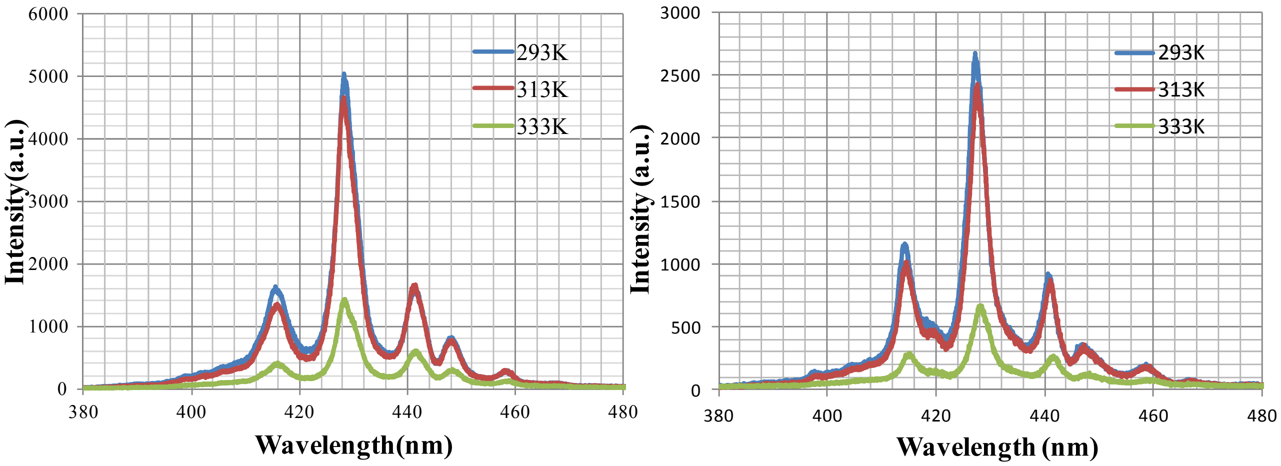


Figure 5. Emission spectra of 10-µm-diameter RCLED at various current levels



(a) (b)

Figure 6. Emission spectra at three ambient temperatures of 293, 313 and 333K under on-wafer junction-side-up testing: (a) 20-µm-diameter device at a fixed current of 10 mA, and (b) 10-µm-diameter device at a fixed current of 5 mA

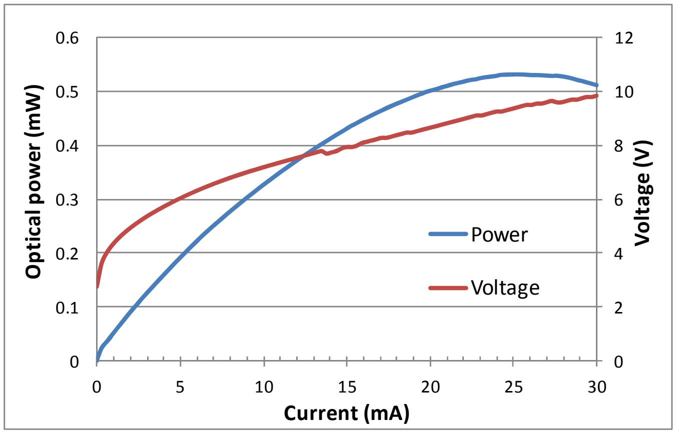
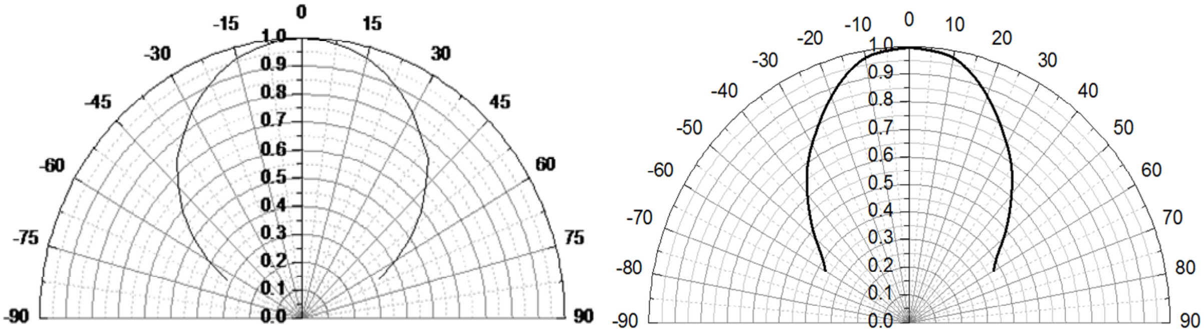


Figure 7. L-I-V curve of 20-µm-diameter RCLED at room temperature



(a) (b)

Figure 8. Comparison of the far-field patterns of (a) 10-µm-diameter LED, and (b) 10-µm-diameter RCLED with a top reflector of 50% reflectance

4. CONCLUSION

GaN-based blue RCLEDs featuring a Si-diffusion-defined confinement structure and a top reflector of 50% reflectance were fabricated and characterized. An output power of 0.53 mW CW at an injection current of 25.2 mA from a 20-μm-diameter RCLED was achieved under probe testing at room temperature. CCD images exhibited bright spots of sizes corresponding to the diffusion-defined aperture sizes. The FWHM of the emission spectrum was reduced from 20 nm to 3.5-4.5 nm after depositing the top reflector, and remained stable when driven at a high current density up to 12.7 kA/cm^2 as well as at a high ambient temperature up to 60°C. The peak wavelength was approximately 428 nm with a small temperature coefficient of less than 0.03nm/°C in terms of the peak wavelength shift per degree of temperature increase. The far-field patterns exhibited half-power angles of approximately 45° indicating superior directionality than conventional LEDs.

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