GaN-Based High-Q Vertical-Cavity Light-Emitting Diodes

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***Abstract*—We report a fabrication and demonstration of a GaN-based high-Q vertical-cavity light-emitting diode (VCLED). The GaN VCLED is composed of a 25-pair high-reflectivity (98%) GaN/AlN distributed Bragg reflector (DBR), an eight-pair SiO_2/Ta_2O_5 dielectric DBR (99%), and a three-λ optical thickness InGaN/GaN active region. It shows a very narrow linewidth of 0.52 nm, corresponding to a cavity Q-value of 895 at a driving current of 10 mA and a dominant emission peak wavelength at 465.3 nm. In addition, this VCLED emission linewidth continues to decrease with an increasing injection current, suggesting a possible realization of GaN-based vertical-cavity surface emitting lasers.**

***Index Terms*—GaN, light-emitting diode (LED), vertical cavity, vertical-cavity LED (VCLED).**

I. Introduction

OVER THE PAST few years, GaN-based materials have been attracting a great deal of attention due to the large direct band gap and promising potential for optoelectronic devices, such as light-emitting diodes (LEDs) and laser diodes [1]. Recently, much effort was devoted to the development of GaN-based vertical-cavity surface emitting laser (VCSEL) [2], [3] because the VCSEL possesses many advantages over edge emitting lasers, including circular beam shape, light emission in the vertical direction against the junction, and formation of 2-D arrays. However, electrically pumped VCSELs are not yet realized nowadays. Recently, Song *et al.* [4] demonstrated a vertical-cavity LED (VCLED) with high-reflectivity dielectric distributed Bragg reflectors (DBRs), using a lift-off technique to separate an InGaN p-n-junction thin film from a sapphire substrate, which led to a complex fabrication process. Diagne *et al.* [5] fabricated a VCLED with a 60-pair $GaN/Al_{0.25}Ga_{0.75}N$ DBR and obtained a narrow linewidth (0.6 nm) emission. However, their devices required a large number of $Al_xGa_{1-x}N$/GaN pairs due to the use of relatively low refractive index contrast in those material combinations. In contrast, a material combination of AlN/GaN has a higher refractive index contrast ($\Delta n/n = 0.16$) that can achieve high reflectivity with a relatively fewer number of pairs. We recently combined a high-reflectivity AlN/GaN DBR with only 25 pairs and a dielectric mirror to form a GaN-based VCSEL and observed a lasing action that is optically pumped at room temperature [6], [7]. By using such a hybrid DBR configuration, in this letter, we report the fabrication of a high-Q ($\sim$895) VCLED comprising a high-reflectivity AlN/GaN DBR, an InGaN/GaN active region, an indium–tin–oxide (ITO) transparent current-spreading layer, and a Ta_2O_5/SiO_2 DBR, and we observe a very narrow linewidth emission.

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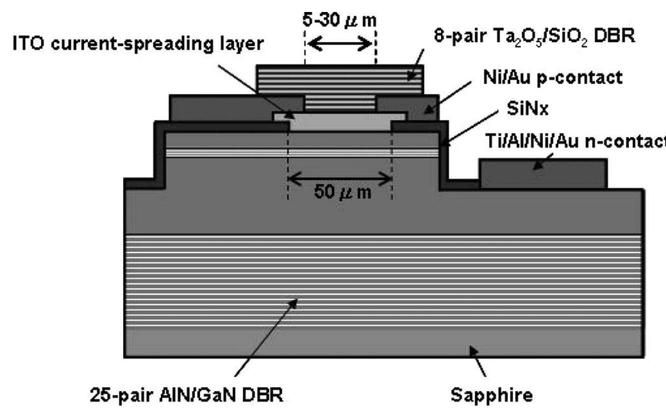

Fig. 1. Overall VCLED structure.

II. Device Fabrication

Fig. 1 shows the schematic diagram of the overall VCLED structure. The sample was grown by a metal-organic chemical vapor deposition system on a polished optical-grade c-face (0001) 2-in-diameter sapphire substrate. Following the growth of a GaN buffer layer, a 25-pair AlN/GaN DBR was deposited and *in situ* monitored at a fixed wavelength of 460 nm. Finally, a three-λ optical thickness ($\lambda = 460$ nm) active p-n-junction region, which is composed of ten $In_{0.2}Ga_{0.8}N$ (3 nm)/GaN(6 nm) multiple quantum wells, a 380-nm-thick Si-doped n-type GaN, and a 100-nm-thick Mg-doped p-type GaN layers, were grown atop the GaN/AlN DBR. A sample with only a 25-pair AlN/GaN DBR was also grown for reflectivity measurement. A peak reflectivity of 98% was measured, with a spectral width of the maximum reflectance band of $\sim$25 nm. The process of the VCLED began with the deposition of a 0.3-μm-thick SiN_x etching mask by using plasma enhanced chemical vapor deposition and the definition of the mesa region by photolithography. The mesa etching was then performed with Cl_2/Ar as the etching gas in an inductively coupled plasma (ICP) reactive-ion-etching system, with the ICP and bias powers operated at 13.56 MHz. After removing the etching mask,

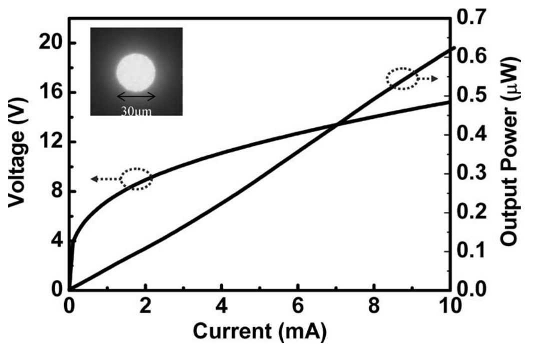

Fig. 2. Current versus voltage and light output power of the VCLED with an emission aperture size of 30 μm in diameter. The inset shows the top-view image of the device with an emission aperture of 30 μm.

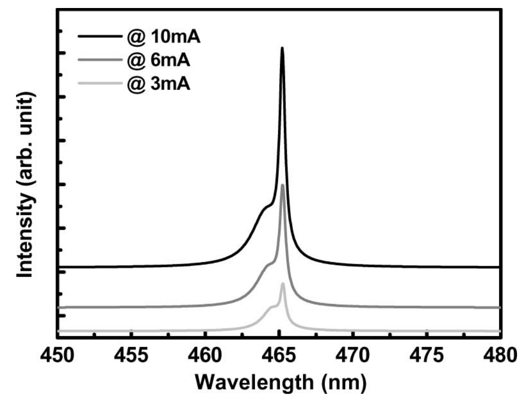

Fig. 3. Emission spectrum of the VCLED operating at three different currents (3, 6, and 10 mA).

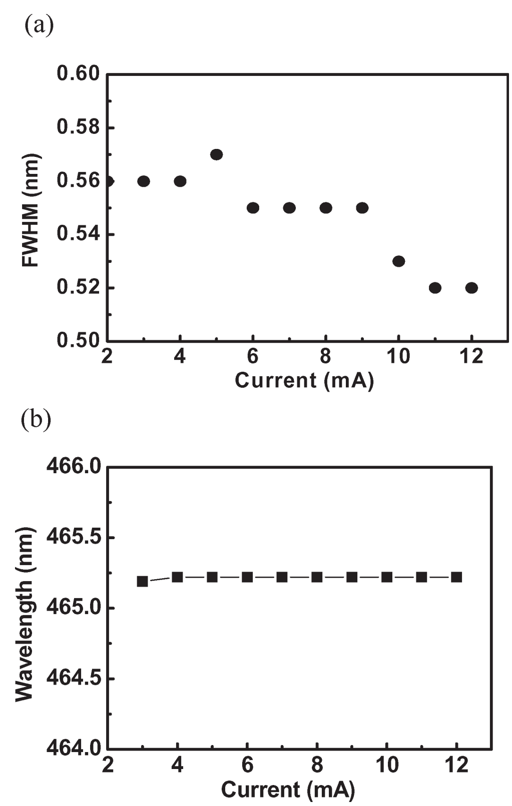

Fig. 4. (a) Linewidth and (b) wavelength of the emission as a function of the injection current.

we redeposited and patterned a 0.2-μm-thick SiN_x layer to define a current aperture of 50 μm in diameter. Then, a 240-nm-thick layer of ITO that corresponds to one-λ optical thickness was deposited onto the current aperture region using an e-gun. The ITO was employed as a p-type ohmic contact material and annealed at 525 °C for 10 min under a nitrogen ambient to reduce the contact resistance and to increase transparency. Over 98% of the transmittance was obtained at $\lambda = 460$ nm after annealing. The metal contact layers were then patterned by a lift-off procedure and deposited onto samples by electron beam evaporation. Ti/Al/Ni/Au (20/150/20/150 nm) and Ni/Au (20/150 nm) served as the n-type electrode and p-type electrode, respectively. A 30-μm emission aperture was formed by lifting off the p-type metal atop the ITO layer. Finally, an eight-pair Ta_2O_5/SiO_2 DBR (a measured reflectivity of over 99% at $\lambda = 460$ nm) was evaporated as the top mirror to complete the VCLED device.

III. Device Characteristics

The characteristics of the fabricated VCLED were performed by using a probe station and driven by a Keithley 238 CW current source. The VCLED light output power was measured by using an integrating sphere with a calibrated large-area Si photodiode at room temperature. Fig. 2 shows the current versus voltage and the light output power of a fabricated device at room temperature. The turn-on voltage of the VCLED was about 3.5 V, indicating a good electrical contact of the ITO transparent layer. However, the relatively high resistance $(530\ \Omega)$ of the device could be due to a nonoptimized growth condition of n-type GaN layer on top of the AlN/GaN DBRs, which further limited device operation at a higher current density. As shown in Fig. 2, the light output power of the VCLED shows a nearly linear increase, with a current of up to 10 mA, without a thermal rollover in this current range. The inset shows the emission image of the VCLED that is operated at an injection current of 6 mA. As the current increased beyond 10 mA, thermal rollover began, and the output power started to saturate, which is probably due to the high serial resistance of the device.

The emission light was then collected in a 25-μm-diameter multimode fiber by using a microscope with a 40$\times$ objective and was then fed into the spectrometer with a spectral resolution of 0.15 nm. Fig. 3 shows the emission spectrum of the VCLED that operates at three different current (3, 6, and 10 mA). As the injection current was increased, a single emission peak at 465.3 nm became dominant, with a rapidly increasing intensity and a narrowing linewidth. The variation of the emission linewidth with the increasing current is shown in Fig. 4(a). The full width at half maximum of the emission linewidth decreased from 0.57 to 0.52 nm as the driving current was increased to 10 mA, which is, to our best knowledge, the narrowest linewidth recorded for GaN-based VCLEDs. The narrowest in the previous report was about 0.6 nm [4], [5]. From the emission peak wavelength at $\lambda = 465.3$ nm and the emission linewidth at $\Delta\lambda = 0.52$ nm, the cavity Q is estimated by $\lambda/\Delta\lambda$ to be ranging from 816 to 895. Since the cavity Q that is formed by our vertical cavity with both high-reflectivity DBRs ($R = 98\%$ and 99%) and ITO current-spreading layer was calculated to be about 890, without taking into account the absorption in the InGaN/GaN p-n-junction region, the narrowing linewidth that is observed represents that the active region was approaching the transparency condition before lasing. The possibility of a GaN-based VCSEL could be realized by a future optimization of higher DBR reflectivities and ITO transparency, lower resistive heating, and better lateral mode confinement. In comparison with conventional LEDs with a spectral linewidth of about 20 nm, our high-Q VCLED has demonstrated a rather coherent emission. Fig. 4(b) shows the emission peak wavelength as a function of the current, which was almost invariant with an increasing injection current, demonstrating a potential in temperature-sensitive applications. These results indicate that our high-Q VCLED has a stable emission wavelength and a narrow linewidth property.

IV. Conclusion

In conclusion, we fabricated a high-Q GaN-based VCLED with a 25-pair high-reflectivity AlN/GaN DBR $(R = 98\%)$, a three-λ optical thickness $In_{0.2}Ga_{0.8}N$/GaN active p-n-junction region, an ITO transparent current-spreading layer, and an eight-pair SiO_2/Ta_2O_5 DBR $(R = 99\%)$. The VCLED showed a very narrow linewidth of 0.52 nm, which is equivalent to a cavity Q-value of 895 at a driving current of 10 mA and a dominant emission peak wavelength at 465.3 nm. The VCLED also showed an invariant emission peak wavelength with a varying current. The results in this letter should be promising in developing GaN-based VCSELs.

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