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Fabrication of High Qualify factor of GaN-based Vertical-cavity Light Emitting Diodes with AlN/GaN and Ta_2O_5/SiO_2 Hybrid Mirrors

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1. Introduction

In the last decade, GaN-based materials and its relative alloy such as AlGaN and InGaN have been attracting much attention due to the wide band gap in visible light and variation application for optoelectronic devices [1]. Recently, the signification of GaN-based vertical-cavity surface emitting laser (VCSEL) shows gradually [2], [3] because the VCSEL possesses many advantages over edge emitting lasers including circular beam shape and formation of 2-D arrays. However, the GaN-based VCSEL did not fabricate in previous years. The key problems limiting the development of GaN-based VCSELs are due to the lack of suitable substrates and the difficulty in growing high-quality and high-reflectivity GaN-based distributed Bragg reflectors (DBRs). Fortunately, Y. Higuchi et. al. at Nichia Corporation and our groups has successfully fabricated the GaN-based VCSEL with double dielectric mirrors and hybrid mirrors by current injection, respectively [4], [5]. However, the VCSEL with double dielectric mirrors has achieved at room temperature, but the devices with hybrid mirrors only has the lasing phenomenon at 77K.

In order to improve the performance of VCSEL with hybrid mirrors, in this letter, we redesign the structure especially in the transparent current spreading layer. The vertical cavity light emitting diodes (VCLED) comprising AlN/GaN DBRs, a n-GaN layer, InGaN/GaN multi-quantum wells, a p-AlGaN layer, the transparent current spreading layer of 30-nm ITO, and Ta_2O_5/SiO_2 DBRs. The thinner 30nm ITO layer can be compensated the phase in the un-uniform cavity and design in the node of longitude modes of the devices. Therefore, the loss of ITO is no longer a problem. Furthermore, the devices use the ITO deposited by sputter which show great electrical properties than that by e-gun. Finally, we can reduce the resistance of the VCLED from 530Ω to 60Ω that shows great performance of the high quality factor of about 1750.

2. Device Fabrication

Fig. 1(a) shows the schematic diagram of the overall VCLED structure and its relative CCD image. The VCLED device was grown by a metal-organic chemical vapor deposition system on a c-face (0001) 2-in-diameter sapphire substrate. The structure was grown of a GaN buffer layer, a 25-pair AlN/GaN DBR, a active p-n-junction region including ten-pairs $In_{0.2}Ga_{0.8}N$ (2.5 nm)/GaN(10 nm) multiple quantum wells, a 680-nm-thick Si-doped n-type GaN, a 25-nm-thick p-type AlGaN layers, and 115-nm-thick p-type GaN. The AlN/GaN DBR has a peak reflectively of 99% located at 440nm, with a spectral width of the maximum reflectance band of about 25 nm. The process of the VCLED was deposited of a 0.2-μm-thick SiNx by using plasma enhanced chemical vapor deposition (PECVD) and etching by inductively coupled plasma (ICP) reactive-ion-etching system. Then, a 30-nm-thick layer of ITO was deposited as a current spreading layer by sputter. The ITO layer was played the role as a p-type ohmic contact material and annealed at 600 ◦C for 10 min under nitrogen ambient to reduce the contact resistance. 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 Ta2O5/SiO2 DBR (a measured reflectivity of over 99% at λ = 440 nm) was evaporated as the top mirror to complete the VCLED device. Fig. 1(b) is the CCD image of VCLED under 2mA at room temperature. The inside circles show the relative structure including the p-contact, the SiNx aperture layer, and the top DBR. According to the better current spreading property of p-GaN, we found the current would flow through the aperture by the 30nm-thick ITO layer and spread in the larger area than the limiting of the aperture. Then, the VCLED would emit the light from the whole structure. Besides, in the aperture, we further found many brightest spot which represented the indium inhomogeneous phenomenon. The brightest spot size is similar to the results of Nichia and our group of about 2 or 3 μm.

3. Device Characteristics

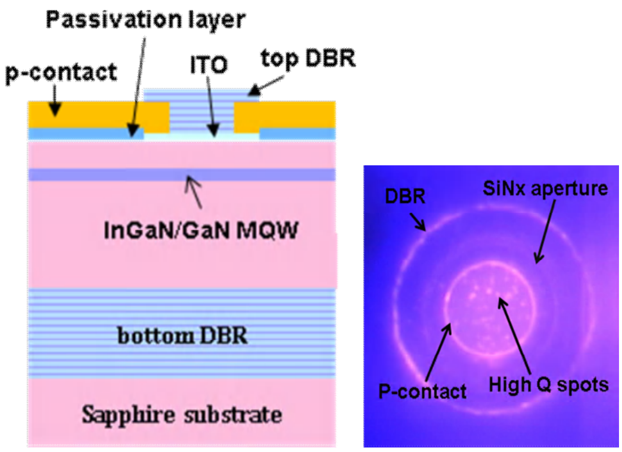

Fig. 1 (a) VCLED structure; (b) CCD image at 2mA

The characteristics of the 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 an integrating sphere with a calibrated large-area Si photodiode at room temperature. Fig. 2 shows the current (I) versus voltage (V) and the light output power (L) of the VCLED device at room temperature. The turn-on voltage of the VCLED was about 5V. The higher turn-on voltage might be caused by non-optimized parameters in the fabrication process. However, from the I-V curve, the devices show the lower resistance of about 60Ω which is better than previous result of about 530Ω [5]. Even in the smaller aperture devices ranging from 5 μm and 25 μm, the resistance of the whole structure still less than 100Ω which make our devices can operate to 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 30 mA without a thermal rollover in this current range. When the current injection is up to 30mA, the light output intensity would decrease due to the thermal effect and then saturated. In our measurement system, the emission spectrum was collected in a 25-μm-diameter multimode fiber by a microscope with a 40× objective and was fed into the spectrometer with a spectral resolution of 0.15 nm.

Fig. 3 shows the emission spectrum of the VCLED under three different current injections of about 5, 10, and 15 mA. When the current was increased, one dominated wavelength was located at 436nm with a lightwidth of about 0.25nm. The quality factor of cavity Q is estimated by $\lambda/\Delta\lambda$ between 1550 and 1750. The VCLED has smaller linewidth of about 0.25nm than the LED linewidth of about 20nm. It means the devices has the great coherent emission by the top and bottom DBR. These results indicate that our high-Q VCLED has a stable emission wavelength and a narrow linewidth property. The characteristic of devices has great potential to be the GaN-based VCSEL with hybrid mirrors operated at room temperature if we keep improved the reflectance of top and bottom DBR, lower resistive cavity, and better ITO transparency and electrical injection layer.

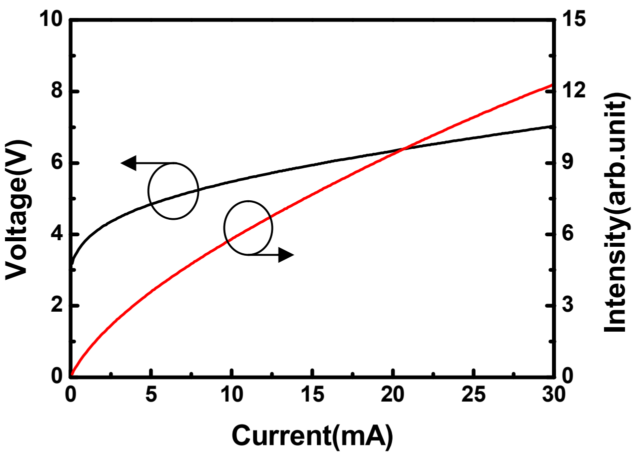

Fig 2 LIV curves of GaN-based micro-cavity light emitting diode with hybrid mirrors

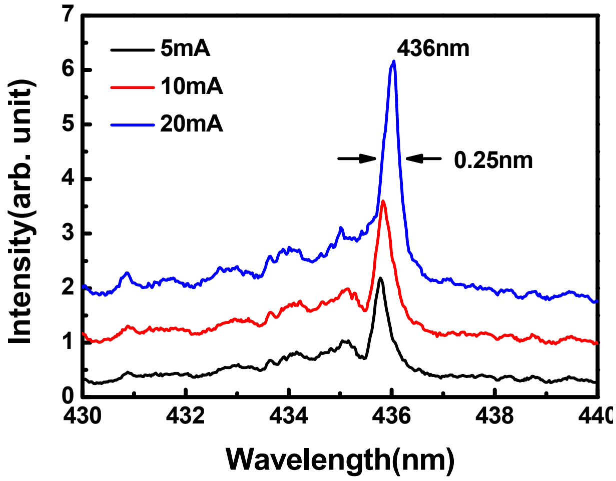

Fig 3 shows the emission spectra under four different pumping energies.

4. Conclusions

We fabricated a high-Q GaN-based VCLED with a AlN/GaN and Ta2O5/SiO2 hybrid mirrors. The devices showed a very narrow linewidth of about 0.25 nm equal to a high-quality factor of about 1750 with a dominant wavelength at 436 nm. The VCLED showed great potential and promising to be the first GaN-based VCSEL with hybrid mirrors operated at room temperature.

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