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High-Power Eu-Doped GaN Red LED Based on a Multilayer Structure Grown at Lower Temperatures by Organometallic Vapor Phase Epitaxy

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ABSTRACT

A modification of the growth structure of Eu-doped GaN (GaN:Eu) from a monolayer to a multilayer structure (MLS) consisting of alternating GaN and GaN:Eu, was shown to enhance the emission properties. Similarly, lowering the growth temperature of the GaN:Eu to 960°C nearly doubled the photoluminescence emission intensity, and also enhanced device performance. Hence, to design a higher power GaN:Eu red LED, a multilayer structure consisting of 40 pairs of alternating GaN and GaN:Eu was grown at 960°C. This combination resulted in the fabrication of an LED with a maximum output power of 110 μW, which is 5.8 times more output power per GaN:Eu layer thickness as compared to the best previously reported device. Moreover, it was found that the MLS sample grown at 960°C maintained a high crystal quality with low surface roughness, which enabled an increase in the number of pairs from 40 pairs to 100 pairs. An MLS-LED consisting of 100 pairs of alternating GaN/GaN:Eu layers was successfully fabricated, and had a maximum output power of 375 μW with an external quantum efficiency of 4.6%. These are the highest values reported for this system.

INTRODUCTION

Wide bandgap III-nitride materials, such as gallium nitride (GaN), have been given considerable attention due to their ability to produce intense emission in the visible and near infrared wavelength regions. Although blue and green light-emitting diodes (LEDs) based on GaN have already been commercialized, nitride-based LEDs in the shorter wavelength region from red to infrared are still premature in terms of intensity. In order to extend the emission wavelength from GaN-based devices, large In compositions are needed to sufficiently reduce the GaN bandgap. However, the low miscibility of In in GaN limits its composition, therefore the growth of InGaN layers with a high In composition and good crystalline quality remains a challenge [1]. Although red LEDs based on InGaN/GaN multiple quantum wells (MQW) have recently been developed [2,3,4], the spectral position and full width at half maximum (FWHM) of the red emission changed with increased injection current. To circumvent the challenges associated with InGaN, Eu-doped GaN (GaN:Eu) based red LEDs have been developed [5,6,7]. These devices exhibit sharp emission lines with a spectral position and FWHM that are not influenced by current injection. These properties make GaN:Eu a promising material for fabricating all GaN-based monolithic active displays, which consist of blue, green, and red LEDs. Unfortunately, the lack of sufficient output power from GaN:Eu based LEDs remains a barrier for practical use. Although several improvements have resulted in a maximum output power of 93 μW,[8] further optimization of the growth conditions and active layer structure are still necessary.

Recently, it was found that the use of a new Eu precursor ($EuCp^{pm}{}_2$) with a lower growth temperature of 960°C reduced the surface roughness of GaN:Eu samples, and led to an enhancement of the integrated emission intensity. However, the photoluminescence (PL) emission spectra was quite broad, which was attributed to significant variations in the local defect structure around certain Eu ions, which may inhibit their optical activity [9]. A delta doped multilayer structure (MLS) containing 40 pairs of alternating GaN/GaN:Eu was recently shown to significantly increase the emissivity of Eu^{3+} ions [10]. This is similar to the results reported for Er-doped Si MLS samples, where it was also suggested that the MLS led to a reduction in the variation of local defect environments around the Er ions [11].

Thus, the next step toward a higher power GaN:Eu based LED was to combine the lower temperature growth with the delta doping structure, and grow GaN:Eu MLS at 960°C (LT-MLS). It was found that introducing the LT-MLS further enhanced the optical activity of the Eu ions, and also had a positive influence on the growth properties of GaN:Eu. In this contribution, we will exploit the impact of the LT-MLS on the growth of GaN:Eu by increasing the scale of LT-MLS LEDs from 40 pairs to 100 pairs, and explore the resulting optical and electrical properties.

EXPERIMENTAL

Two LEDs were fabricated on (0001) sapphire substrates by OMVPE using the growth structure and procedure explained in detail in ref. 5 and 9, but with the 300nm GaN:Eu layer replaced by a MLS region containing 40 pairs and 100 pairs of alternating GaN (6 nm) and GaN:Eu (3 nm) layer stacks. The GaN:Eu MLS regions were grown at 960°C using trimethylgallium and ammonia as starting sources, and $EuCp^{pm}{}_2$ as the Eu source. During growth, the surface roughness of the samples was monitored by Laytec, which is an in-situ monitoring system.

To explore the optical properties, PL was measured by exciting the Eu^{3+} ions with the 325 nm line of a He-Cd laser at room temperature. The PL emission spectra were collected using a 0.5 m spectrometer equipped with a charge coupled device (CCD). The total light output power of the LEDs was measured using an integrating sphere spectrometer (Labsphere/LMS-100).

RESULTS AND DISCUSSION

As shown in Fig. 1, the PL emission spectra of the GaN:Eu LT-MLS LED sample containing 40 pairs was more resolved than that of the LED with a 300nm monolayer of GaN:Eu grown at 960°C (300nm bulk), and exhibited a higher emission intensity. More importantly, the LT-MLS sample had roughly one third the total GaN:Eu thickness as compared to the 300 nm bulk sample, which indicates that the PL intensity per GaN:Eu layer thickness was enhanced by at least a factor of three. Thus, the LT-MLS further increased the optical activity of the Eu ions, as expected.

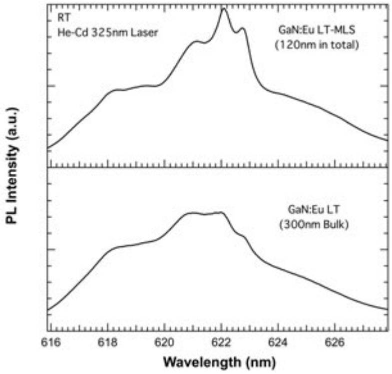

Fig. 1 PL emission spectra of a GaN:Eu LT-MLS LED containing 40 pairs and a GaN:Eu LED with a single 300nm thick active layer.

Next, the emission of the LT-MLS LED with 40 pairs and the 300nm bulk LED grown at 960°C were compared under current injection (Fig. 2). The LT-MLS LED had a significantly higher maximum output power of ~110 μW, compared to 48 μW from the 300nm bulk LED.[9] Again, since the total GaN:Eu layer thickness was a factor of three lower for the LT-MLS LED, this means that the output power per GaN:Eu layer thickness was 5.8 times higher. This promising result indicated that an even higher output power could be achieved by increasing the number of pairs in the LT-MLS LED, as long as the output power scaled with the number of pairs. However, increasing the number of pairs could have a negative impact on crystal quality due to increased strain within the layers, which could disrupt the surface morphology during growth.

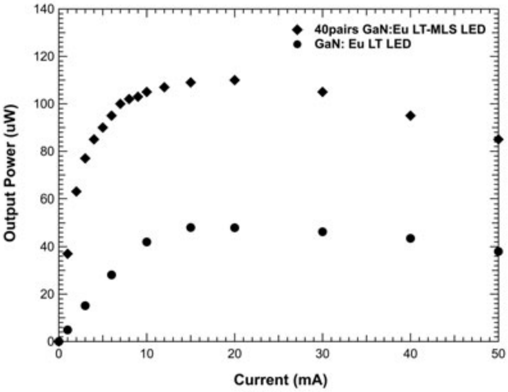

Fig. 2 Comparison of the output power versus injection current between a LT-MLS LED containing 40 pairs (squares) and a 300nm bulk LED (dots).

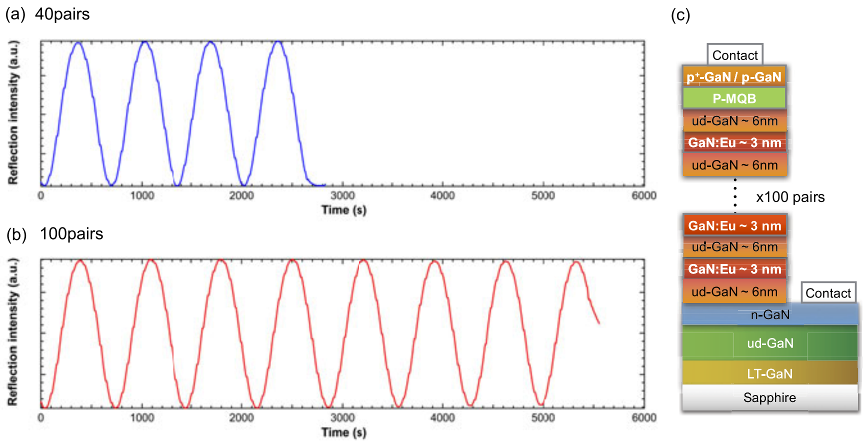

Fig. 3 (a) The in-situ reflection curve of the LT-MLS LED containing 40 pairs. (b) The in-situ reflection curve of the LT-MLS LED containing 100 pairs. (c) Device diagram of the LT-MLS LED containing 100 pairs.

To explore the impact of the MLS structure on the growth of the samples, the quality of the sample surface was monitored in-situ using the reflectivity curves given by the Laytec monitoring system. Figure 3(a) shows the reflectivity curve of the LT-MLS containing 40 pairs. The reflectivity amplitude does not diminish over time, which means that the growth of 40 pairs of alternating GaN/GaN:Eu does not disrupt the quality of the sample surface. This result, along with the enhanced optical activity of the LT-MLS, suggests that increasing the total number of pairs is a suitable path for higher output power. Thus, an LT-MLS LED containing 100 pairs was fabricated. This LED had a total GaN:Eu layer thickens of 300 nm, which is the same as the 300nm bulk LED. The reflectivity of the LT-MLS containing 100 pairs was also monitored during growth, and is shown in Fig. 3(b). As expected, the reflectivity amplitude does not diminish over time, which suggests that LT-MLS with 100 pairs maintained a high surface quality during growth. The structure of this LED is shown in Fig. 3(c).

Next, the performance of the LT-MLS LED with 100 pairs was explored. Fig. 4(a) shows the I-V curve of this LED. The turn-on voltage was relatively high since the total active layer was rather thick (900nm). However, despite the thickness of the active layer, the LED did exhibit a typical diode behavior. Furthermore, the room temperature electroluminescence spectra from LED was dominated by ~622 nm emission originating from the Eu^{3+} ions, and remained constant as the current was increased from 1 mA to 20 mA (Fig. 4(b)). The output power of the LED increased with higher injection currents, and reached a peak output power of 375 μW under an injection current of 20 mA. However, when the injection current was increased to higher than 20 mA, the output power went down as the result of thermal quenching. Fig. 4(c) shows the external quantum efficiency (EQE) versus injection current. The maximum EQE was 4.6% at 1 mA, which is higher than that reported for InGaN/GaN red LEDs [4], and further demonstrates that the GaN:Eu LT-MLS LED is a promising candidate for GaN-based red LEDs.

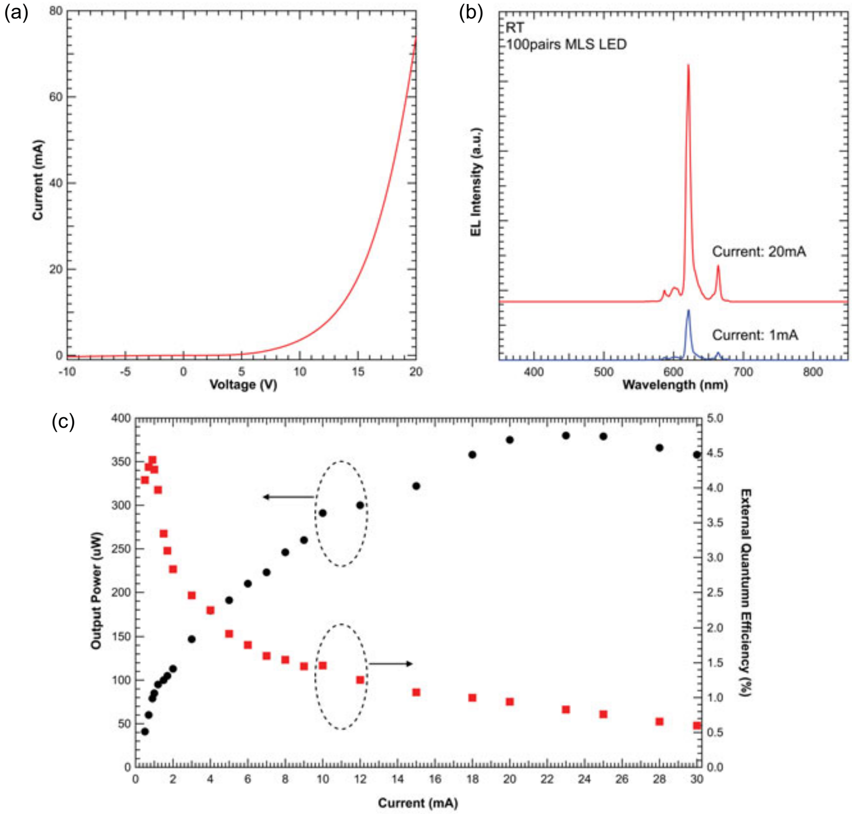

Fig.4 (a) I-V curve for the GaN:Eu LT-MLS LED containing 100 pairs. (b) The room temperature electroluminescence is dominated by the 622 nm emission from the Eu^{3+} ions, and does not vary with increased current injection. (c) The output power and external quantum efficiency from the GaN:Eu LT-MLS LED with 100 pairs as a function of injection current.

CONCLUSIONS

We have successfully demonstrated the impact of introducing a multilayer structure for GaN:Eu samples grown at 960°C. LEDs fabricated with the LT-MLS resulted in a significant improvement on device performance, as compared to a reference LED with a 300 nm thick GaN:Eu monolayer grown at 960°C. The LT-MLS was also found to maintain the reflectivity curve of GaN:Eu samples during growth, as measured by Laytec. This result allowed for the number of pairs of GaN/GaN:Eu to be scaled up from 40 to 100, with a negligible impact on the growth quality and surface roughness. An LT-MLS LED containing 100 pairs of GaN/GaN:Eu layers was successfully fabricated, and was found to have a maximum output power of 375 µW and an EQE of 4.6%. These values are the highest reported for the GaN:Eu system. Thus, the LT-MLS is a promising sample structure for the realization of GaN:Eu based red LEDs.

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