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Developments of High Efficiency InGaN-Based Light-Emitting Diodes

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1. Introduction

The quest for environment friendly and energy saving technologies has propelled the advancement of light-emitting diodes (LEDs) for solid-state lighting. High efficiency LEDs, especially GaN-based white light LEDs, become the subject of intensive research worldwide. There have been various technologies tackling different aspects of the luminous properties of GaN-based LED proposed in the past few years. Increasing external quantum efficiency is naturally one of the most popular topics. Based on the same techniques for GaAs-based LEDs, GaN LEDs with improved efficiency were also demonstrated by surface roughening [1,2], chip shaping [3], microcavity formation [4], wafer bonding [5,6], and substrate patterning [7]. However, the internal efficiency of GaN-based LEDs decreases markedly as the emission wavelength moves to ultraviolet (UV) range, i.e. 400 nm and shorter, where can be used to pump RGB phosphors for lighting purpose. This reduction of the internal quantum efficiency is believed to be associated with material-dependent luminescence mechanism [8, 9]. Besides, the performance of the Ni/Au semi-transparent conductive layer used in conventional LEDs is also wavelength-dependent and becomes an issue for high power UV LEDs [10]. In this talk, we will present the results of our recent work on these issues, which are essential to achieve high efficiency UV LEDs.

2. Luminescence Properties

The luminescence efficiency of InGaN/GaN quantum well decreases with decreasing InN mole fraction when the emission wavelength is tuned toward ultraviolet range. This was attributed to two fundamental reasons, i.e. less localized effect due to less InGaN composition fluctuation and less carrier confinement due to lower band discontinuity. Although our recent study on 410 nm InGaN/GaN multi-quantum wells shows that bandedge emission indeed dominates over localized states at high current levels [11], it seems that growth parameter and material quality make a difference. To probe further on this topic, we characterize LEDs (300 x300 μm^2) in 400 nm and 470 nm, which correspond to different InN mole fractions in quantum wells. Fig. 1 shows the electroluminescence (EL) integrated intensity of the 400 nm LED driven at various currents. The light output starts to saturate or degrade at a point depending on duty cycle of the driving current. The 470 nm device exhibits the same behavior. It can be concluded that thermal effect instead of carrier overflow effect dominates the luminescence efficiency at high current levels since this point moves to higher current levels when the duty cycle is decreased. More detailed characteristics can be observed from the external quantum efficiency at different current densities shown in Fig. 2. It can be seen that before the thermal effect sets in, the dependence of external quantum efficiency on current density is different for these two devices. It might be related to the carrier confinement, defect density, and localized states in the active region. The implication of this result is twofold. One is the dominant luminescence mechanism for low and high In content quantum wells might be different. The other one is epilayer structure must be optimized for certain chip size and current density with adequate heat dissipation when designing large area LEDs for high flux output.

3. Chip processing

Due to the limited conductivity of p-type cap layer and n-type buffer layer in typical GaN-based LEDs, current crowding effect becomes significant as the chip size is increased. Semitransparent ohmic contacts, such as Ni/Au, Pd/Au, and indium tin oxide (ITO), have been widely used to alleviate this problem. However, the reliability and transmittance of these contacts degrade when they are applied to high power large area UV LEDs. We proposed a p-side down tunneling junction LED structure for this reason [12]. External quantum efficiency as high as 17 % was achieved without using any transparent contact layer. Although current crowding effect still exists in this device, it can be minimized by optimizing the growth and design of the n-type cap and bottom layers. Nonetheless, flip-chip scheme seems to be the most promising approach for high power LEDs [13]. This approach is even more desirable for UV LEDs lighting source since better light extraction and heat dissipation can be achieved this way. A reflective p-type ohmic contact is therefore necessary for flip-chip LED. We have developed an Al-based reflective ohmic contact with about 75 % reflectivity at both 370 and 400 nm. It should be noted that proper layout design is still necessary to ensure uniform current spreading through the n-type layer [14].

4. Summary

We review recent work on the developments of InGaN-based LEDs regarding material characteristics and chip processing, which are essential to realize high power

LEDs for solid-state lighting.

Acknowledgments

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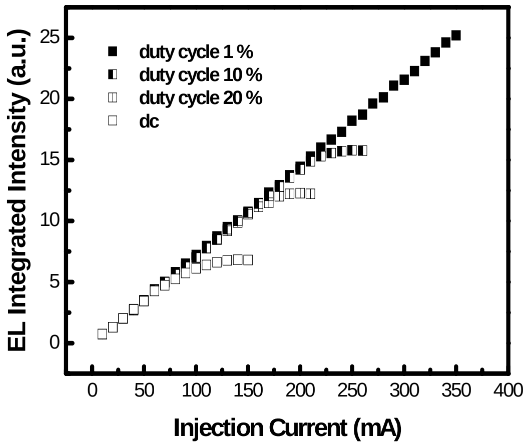

Fig. 1 Electroluminescence integrated intensity of a 400 nm ultra violet LED driven at various currents.

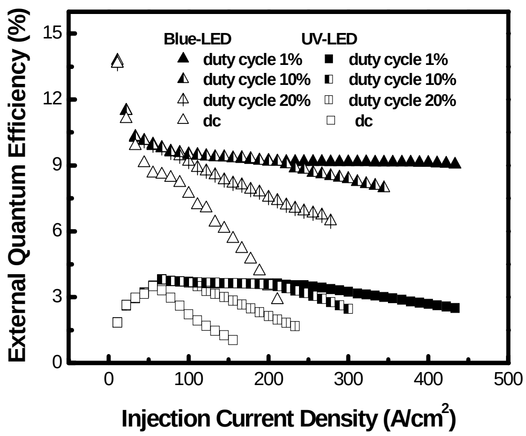

Fig. 2 External quantum efficiency of InGaN/GaN multi-quantum well LEDs driven at various current densities.

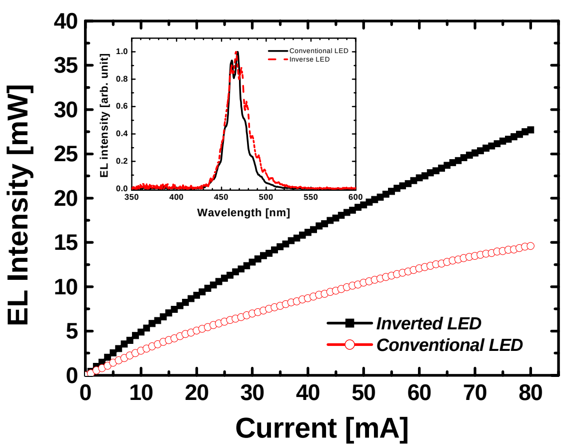

Fig. 3 Light output and spectrum of InGaN/GaN multi-quantum well p-side down tunneling junction LEDs.