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Efficiency droop reduction in GaN-based light-emitting diodes by gradient-thickness multiple quantum wells

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1. Introduction

For potentially higher efficiency than traditional lighting source, solid-state lightings, especially GaN-based light-emitting diodes (LEDs), have been vigorously developed. As the efficiency of LEDs increasing, the upcoming challenge is the efficiency "droop" for high-power applications [1]. The major cause of efficiency droop is still a huge controversy. Several possible mechanisms of droop including carrier overflow [2], non-uniform distribution of holes [3], Auger scattering [4] have been proposed. From our previous research [3], carrier leakage and non-uniform distribution of holes might be the most feasible reasons. Many researchers have proposed several ways to improve droop behavior, such as polarization-matched multiple quantum wells (MQWs) [5], non-polar or semi-polar GaN substrate [6], InGaN barriers [7], but these methods disadvantage either cost, or conduction band offset.

On the other hand, evidences indicated that spontaneous emission only occurs in one or few quantum wells near p-side [8]. This observation confirms that non-uniform distribution of holes and high-carrier-density Auger scattering could be the major problem for GaN-based LEDs. To reduce the droop effect, improving the hole distribution along MQWs would enhance the recombination efficiency of electrons and holes and avoid high carrier density at certain number of wells leading to Auger scattering.

Other group also pointed out that carrier transportation and distribution could be modified by varying indium content or width of quantum wells [9]. In this research, we design a LED with graded-thickness multiple quantum wells (GQWs). The emission spectrum of GQW LED shows larger blue shift and FWHM than reference. And symmetry of emission spectrum measured by electroluminescence testifies that the radiative recombination distribution is improved by graded-thickness design, and the droop behavior is reduced.

2. Experiments

The LED structure was grown on c-plane sapphire substrate by metal-organic chemical vapor deposition (MOCVD). A 20-nm-thick low temperature GaN nucleation layer followed by a 4 μm n-type GaN buffer layer, ten-pair InGaN/GaN superlattice were grown on the top of sapphire. After that, six-pair MQWs were grown with 10-nm-thick GaN barriers. For our designed experiment, the reference LED has the same 2.25-nm-thick $In_{0.15}Ga_{0.85}N$ quantum wells, and the thickness of QWs in GQW LED, controlled by growth time, are graded from n-side to p-side, which are 1.5, 1.8, 2.1, 2.4, 2.7, 3 nm, respectively. The total active region volume of these two samples are the same. Finally, a 20-nm-thick electron blocking layer with $Al_{0.15}Ga_{0.85}N$ and a 200-nm-thick p-GaN layer were grown to complete the epi-structure. The LED chip was fabricated by regular chip process, and the size of mesa is 300×300 μm^2.

3. Results and Discussion

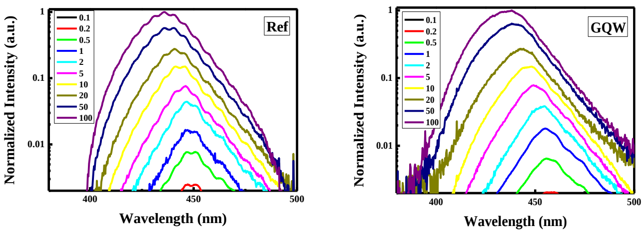

Fig.1. Current-dependent electroluminescence spectrum of (a) reference and (b) GQW LED

Figure 2 (a) and (b) show the current-dependent electroluminescence spectrum of reference and GQW LED, respectively. GQW LED had significant blue shift, 168 meV from 0.1 mA to 200 mA, compared to 90.6 meV of reference, and the FWHM raised 101.4 and 65 meV, respectively. Since the width of well nearest p-side for GQW and reference LED are 3 nm and 2.25 nm, emission from wider well nearest p-side and gradient-thickness wells could both be the occasion of abnormal blue shift and enlargement of FWHM for GQW LED. To investigate the emission characteristic for both sample, we analyzed the power-dependent emission spectrum. If the radiative recombination did happened below the QW nearest p-side, the shape of emission spectrum would reveal some observable clue except blue shift and FWHM. As the carriers started to fill in the narrower wells, bluer light emitted compared to wider wells. As a result, the intensity of shorter part in spectrum was raised, and the symmetry of spectrum might be changed.

To prove the above hypothesis, we investigated the symmetry of spectrum by its tailing factor (T_f). It can be defined as the distance from the center line of the peak to the back slope divided by the distance from the center line of the peak to the front slope, with all measurements made at 50% of the maximum peak height. According to the definition of T_f, if the bluer light emits from narrower wells, the symmetry of spectrum would be interrupted and smaller than 1. We calculated the T_f under every injection level for both sample, as shown in figure 2. From 0.1 mA to 100 mA, T_f of reference LED started at 1.04 (0.1 mA) and saturated at 0.98 (20 mA). But GQW LED showed larger variation, the T_f started at 1.05 (0.1 mA) and saturated at 0.89 (after 20 mA). The significant variation of T_f for GQW LED showed the greater blue shift and FWHM not only because the wider well nearest p-side, but also the additional emission from the following wells.

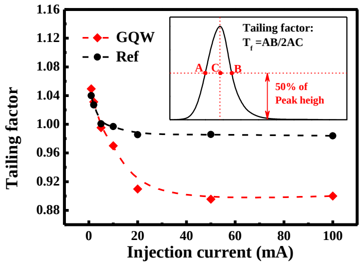

Fig.2. Current-dependent tailing factor of GQW and ref LED.

The normalized efficiency (η) of ref and GQW LED are shown in figure 3. The output power of LEDs was measured by spectrometer, and we integrated the light intensity of emission spectrum. The η_{peak} of reference and GQW LED are at injection current of 10 mA and 50 mA, respectively, indicating that η_{peak} is still dominated by well width, especially the well nearest p-side.

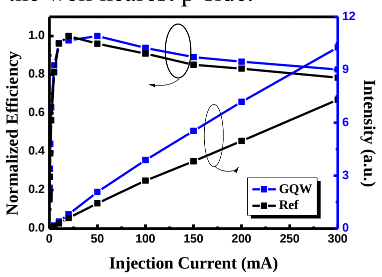

Fig.3. Normalized efficiency and L-I curve of GQW and Ref LED.

The efficiency droop, defined as (η_{peak} - $\eta_{200\ mA}$)/ηpeak, is 17% for reference LED. The small amount of droop for reference is due to the InGaN/GaN superlattice as a strain-relaxed layer. For LED with GQW design, the percentage of efficiency droop is alleviated to 13.3%. This improvement could be mainly attributed to superior radiative recombination distribution, and also the lower carrier concentration in QW nearest p-side (Auger scattering is also reduced). Moreover, the L-I curves were plotted through integrated intensity of spectrum, and the light output power enhancement at 20 mA is 35% for GQW LED. Even with wider wells (worse wave function overlap for electrons and holes) near p-side, the overall efficiency for GQW LED is still higher than reference, which proves that utilization rate of MQWs is improved.

3. Conclusions

In summary, GaN-based LEDs with gradient-thickness multiple quantum wells were investigated both numerically and experimentally. The efficiency droop behavior could be alleviated, 13.3% from η_{peak} to $\eta_{200\ mA}$, compared with 17% of reference, even with. And the light output power is enhanced by 35% at 20 mA. The alleviation in droop and enhancement in output power are mainly attributed to the enhanced hole distribution leading to enhanced radiative recombination distribution. This work implies that with suitable active region design, carrier transportation behavior could be modified, which is very useful for reducing efficiency droop.

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