Methods of Improving GaN based LED Luminous Efficiency

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Keywords: Light Emitting Diodes, droop effect, Nanorods

Abstract

Improving luminous efficiency is a substantial requirement for light emitting diodes (LEDs). To achieve the prospect of energy saving, methods were brought up to improve the internal quantum efficiency and light extraction efficiency. Here we will review technologies which can effectively enhance the efficiency of LEDs base on nanostructures and improved epi-structures.

INTRODUCTION

Currently, GaN based light emitting diodes (LEDs) are the core technology for solid state lighting. It is predicted that in the near future GaN LEDs will significant penetrate the general lighting market. For this purpose, high efficiency, high brightness, and most importantly, low cost are the fundamental requirements for GaN based solid state lighting. There are several key parameters to benchmark the performance. Recent research has heavily focused on improving the external quantum efficiency (EQE), which is commonly defined as the product of the injection efficiency, the internal quantum efficiency (IQE) and the light extraction efficiency (LEE). The IQE is basically influenced by nonradiative recombination processes, caused by dislocations and other defects, and by separation of the electron and hole wave functions by spontaneous polarization and strain-induced piezoelectric polarization. The LEE is limited by the total internal reflection of generated light due to the high refractive index difference between LED structures and air and successive re-absorption.

In this paper, we will review several approaches to enhance the efficiency which includes improving IQE and LEE as well as reducing the droop effect, as being illustrated in Fig 1.

DISCUSSION

Owing to the large mismatch of lattice constant and thermal expansion coefficient between epitaxial GaN films and sapphire substrates, high-density dislocations ranging from10^8 - 10^{10} cm^{-2} degrade the light-emitting diode (LED) performance profoundly. Epitaxial lateral overgrowth (ELOG) was effective to reducing the number of dislocations in the GaN epitaxial layers [1]. Besides, the patterned sapphire substrate (PSS) can also improve IQE by reducing the dislocation density and the geometrical shape on sapphire substrate can effectively enhance light extraction efficiency by scattering or redirecting the guided-light inside an LED chip to find escaping cones [2]. The dislocations can also be reduced by growing homoepitaxially on a bulk GaN substrate [3]. In this case, additional process steps, such as surface nitridation and low-temperature buffer layer which are mandatory in heteroepitaxial growth, are not needed. The epitaxial growth procedure is therefore greatly simplified. Additionally, LEDs with a vertical configuration can be fabricated on a conducting GaN substrate, significantly facilitating chip processing and packaging. The vertical geometry in combination with the high thermal conductivity of GaN allows the LEDs to operate at much higher current densities. Another noticeable method to improve IQE is growing GaN on non-polar surface. For GaN based LEDs, as a standard growth technique growth is established on the c-plane leading to lattice mismatch between the InGaN and GaN layers in the active region. As a consequence strain is induced, which creates the internal electric field and results in the separation of electrons and hole and the corresponding reduction of internal quantum efficiency. The phenomenon is called quantum confined stark effect (QCSE). Growth on the non-polar m-plane can eliminate the QCSE effect, the reduction of separation between electrons and holes wave functions will lead to an improvement of IQE for the LED [4].

The IQE of today's best LEDs is at least 75% [5] and may even be approaching 80%. When it comes to the extraction efficiency, because of large differences in the refractive indices of air and the GaN materials system, a considerable fraction (90–95%) of the generated photons within the LED are trapped by total internal reflection. Roughening the top surface of an LED is one of the methods for improving the light extraction [6]. After removing part of the p-GaN material, the underneath InGaN/GaN strain was found to be partially relaxed [7]. The device with flip chip structure and n-GaN structure can further improve the LEE of greater than 100% [8]. Except the GaN surface roughening, the texture structure can also be fabricated on the mesa sidewall [9] or the transparent conducting layer on top surface [10]. With similar concept, nanorods or nanowires were introduced to improve the LEE. The rods can be grown by hydrothermal methods [11], vapor–liquid–solid epitaxy [12], and can be also fabricated by direct etching on p-GaN surface or around mesa [13]. The nanorod arrays have the ability to reshape the beam profile. Compare to the traditional on top structure, the nanorods surround the mesa and act as reflectors to collect the laterally propagating guided modes and cause a light output enhancement [14]. Furthermore, nanorod array can also act as a grating and increased the p-polarized to s-polarized ratio [15]. Perfect ordered nanorod arrays can also be fabricated by e-beam lithography and act as photonic crystals (PhC). The photonic bandgap can further improve the optical output compare to the PhC LEDs with texture effect only [16]. Compare to the typical PhCs on the mesa surface, a combination of PhC structure on the mesa surface and nanohole reflectors surrounding the light-emitting mesa can further enhance the diffraction of low-order modes propagated in the lateral direction [17][18]. Other than the methods above, increasing the density of states and the spontaneous emission rate in the semiconductor by surface Plasmon coupling is also an emerging technique [19].

An important mystery that needs to be solved in the near future is the decrease in EQE when operating at higher current densities (over 10 A cm^{-2}) as trying to increase the luminous flux. The major cause of efficiency droop is still a controversy. Various possible mechanisms of droop including carrier overflow [20], nonuniform distribution of holes [21], Auger scattering [22], and carrier delocalization [23] have been proposed. Although the exact cause has not yet been determined, it is believed that using thicker quantum wells [24] and altering the structure to lessen carrier overflow will reduce the droop effect and may be possible to operate at higher efficacies and currents. Typically there are two epitaxial approaches to reduce the droop effect. One is to suppress the electron overflow, and another one is to improve the hole injection. For the former approach, one can grow GaN on nonpolar substrate to eliminate the QCSE effect [25] or can insert superlattice layer to reduce the strain [26]. For the latter approach, one can grow graded composition layers including electron blocking layer [27]、quantum well [28] and quantum barrier [29], which can improve the hole injection and reduce the electron overflow simultaneously. All the mentioned techniques can reduce the droop effect compare the conventional LEDs and may be candidates for high power application.

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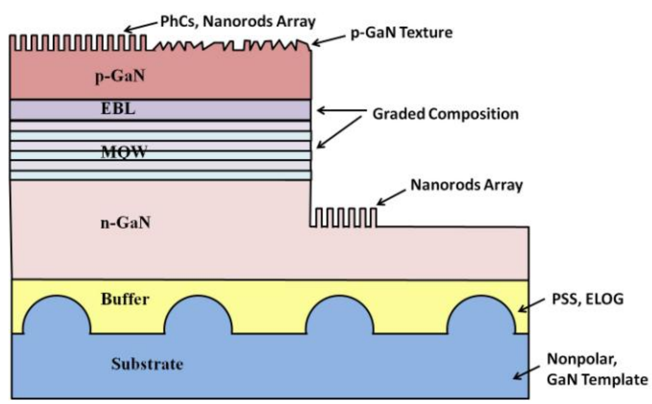

Fig. 1 Typical approaches to enhance the LED efficiency.