Methods of Improving GaN based LED Luminous Efficiency

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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 based 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 significantly penetrate the general lighting market. For this purpose, high efficiency, high brightness, and most important, low cost are the fundamental requirements for GaN-based solid state lighting. There are several key parameters which benchmark LED performance. Recent research has been 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].

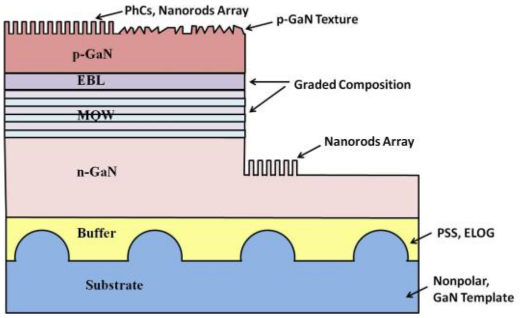


Figure 1: Typical approaches to enhance the LED efficiency

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 a 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 a non-polar surface. For GaN based LEDs, as a standard growth technique originating on the c-plane leads to lattice mismatch between the InGaN and GaN layers in the active region. However, as a consequence, strain is induced, creating an internal electric field and resulting in the separation of electrons and holes subsequently reducing the internal quantum efficiency. This phenomenon is called quantum confined stark effect (QCSE). Growth on a non-polar m-plane can eliminate the QCSE effect, the reduction of wave function separation between electrons and holes, 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 from the raman spectra shown in Fig.2 [7].

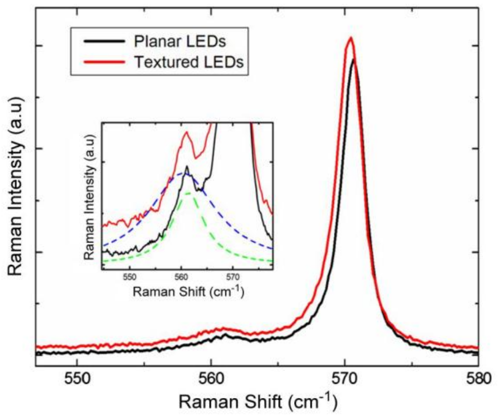


Figure 2: Room-temperature Raman scattering spectra of both (black line) planar and (red line) textured LEDs. Inset: Close-up view of (solid lines) the InGaN E^{H}_{2} modes. The fitting curves are shown in dashed lines.

The device with flip chip structure and n-GaN structure can further improve the LEE of greater than 100% compare to the conventional one [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 as shown in Fig.3 [14].

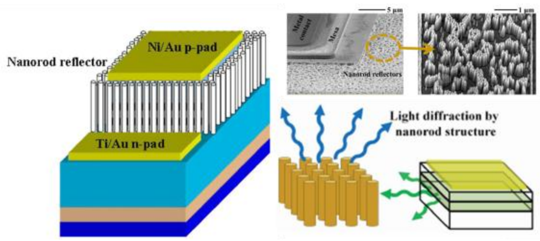


Figure 3: The nanorods surround the mesa can collect the laterally propagating photons.

Light striking onto the nanorod reflectors can be subject to a random-walk type of a forward scattering/diffraction process or a backward process to reenter into the waveguide portion of the mesa. The radiation profile in Fig.4 shows that the nanorod reflector enhances the radiation intensity omnidirectionally. In this case the 20 μm wide nanorod array reflector structure can redirect the laterally propagating wave guided modes of the LED from the light emitting mesa to the air more effectively than a thinner one, as the extraction efficiency of in-plane radiation increases with the width of nanorod reflectors before it saturates.

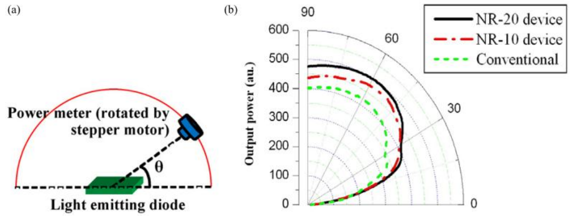
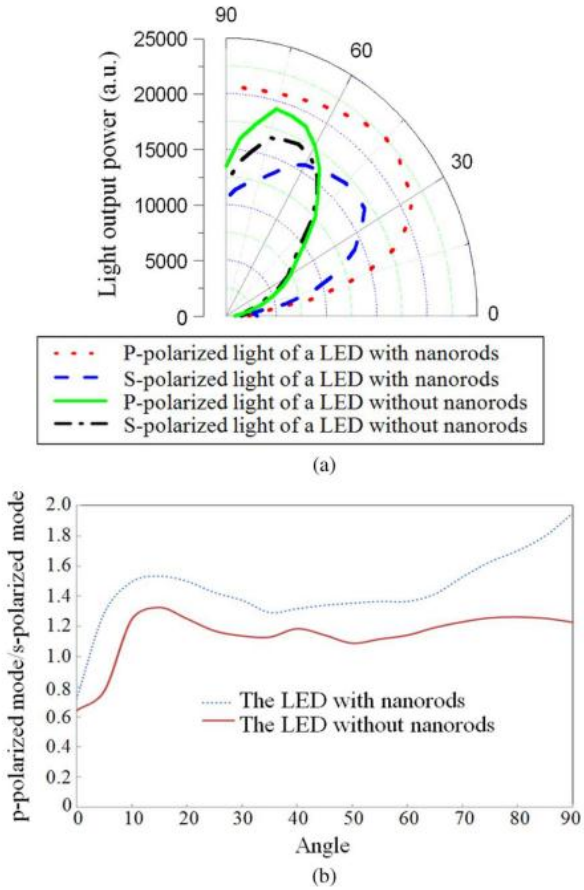


Figure 4: (a) Measurement setup for detecting radiation profiles. (b) Radiation profiles of the conventional device and devices with 20 μm wide and 10 μ m wide nanorod reflectors.

Furthermore, nanorod array can also act as a grating [15]. Since the diffraction efficiency is higher when the incident light is polarized in the direction parallel to the grating grooves, the Bragg diffraction by nanorods of laterally propagated p-polarized mode is more efficient than the s-polarized light. Therefore, the increase of the p-polarized light is more significant than that of the s-polarized as shown in Fig. 5, making the p/s-ratio of the device with nanorods higher than the one without rods. 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 compared 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 proposed possible mechanisms of droop include carrier overflow [20], nonuniform distribution of holes [21], Auger scattering [22], and carrier delocalization [23]. 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 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 a superlattice layer to reduce the strain [26]. For the latter approach, one can grow graded composition layers including electron blocking layer [27] a quantum well [28] and a quantum barrier [29], which can improve the hole injection and reduce the electron overflow simultaneously. All the techniques discussed in this paper, can reduce the droop effect compared to conventional LEDs and may be candidates for high power applications.



(a)

(b)

Figure 5: (a) Radiation profiles of the devices with and without nanorods biasedat an injection current 1 mA. (b) The p/s-polarized ratios at various radiated angles.

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