InGaN light-emitting diodes with naturally formed truncated micropyramids on top surface

J. K. Sheu\textsuperscript{a)}
Advanced Optoelectronic Technology Center and Institute of Electro-optical Science and Engineering, National Cheng Kung University, Tainan, 70101, Taiwan, Republic of China

C. M. Tsai
Institute of Microelectronics & Department of Electrical Engineering, National Cheng Kung University, Tainan, 70101, Taiwan, Republic of China

M. L. Lee
Department of Electro-Optical Engineering, Southern Taiwan University of Technology, No.1, Nantai St, Yung-Kang City, Tainan 710 Taiwan, Republic of China

S. C. Shei
Epitech Technology Corporation, Hsin-Shi 744, Taiwan, Republic of China

W. C. Lai
Institute of Electro-optical Science and Engineering, National Cheng Kung University, Tainan, 70101, Taiwan, Republic of China

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GaN-based light-emitting diodes (LEDs) with truncated micropyramids surfaces performed by metalorganic chemical vapor deposition were demonstrated. In this study, a growth-interruption step and an Mg-treatment process were simultaneously performed to create multiple truncated micropyramids on LED surface. Experimental results indicated that GaN-based LEDs with the truncated micropyramids on the top surface demonstrate improved external efficiency of around 60% at 20 mA. It is worth noting that the typical 20 mA driven forward voltage is only 0.15 V higher than that of conventional LEDs (LEDs with specular surface). © 2006 American Institute of Physics. [DOI: 10.1063/1.2185622]

Solid-state lighting is the use of light-emitting diodes (LEDs) to produce white light for illumination. Similar to semiconductor transistors, which replaced vacuum tubes in electronic circuits, LED application for general lighting is a promising technology that has the potential to displace fluorescent lamps. In order to replace fluorescent lamps, the white LEDs luminous efficiency has to demonstrate at least a twofold increase over present performance measures of commercial white LEDs with typical luminous efficiency of around 30 lm/W. The luminous efficiency of white LEDs, which represent a combination of phosphors and blue (or ultraviolet) LEDs or red, green and blue LEDs, largely depends on the external quantum efficiency of excitation sources (i.e., LEDs). The external quantum efficiency (EQE) of any LED device is determined not only by the internal quantum efficiency, but also by the probability that a photon emitted from the active layer will escape from the high-refractive-index semiconductor material into the lower-refractive-index surrounding material, i.e., air or resin. \textsuperscript{1} In order to improve the light extraction efficiency, much effort is made to overcome significant photon loss resulting from total internal reflection inside the light-emitting diode. In other words, this critical angle is crucially important for the light extraction efficiency of LEDs. To enhance the escape probability of photons generated in the active layer of the LED, large critical angle or rough surface is required. Although the refractive index of a semiconductor cannot be changed, one can enhance light output by roughening the semiconductor surface. For a LED, the angular randomization of photons can be achieved by surface scattering from the roughened top surface of the LED. Therefore, roughening a surface of the light-emitting diode is adopted as a way to overcome the total internal reflection of the light inside the LED. There are many methods to roughen a top surface of the GaN-based LEDs, and one of these methods is performed by etching process. However, etching processes also easily alter the surface state of $p$-GaN layer and thereby degrade the electrical properties of devices.\textsuperscript{2} Therefore, methods of controlling the growth conditions to obtain rough surfaces should be superior to the etching methods. The application of naturally textured surface pits, which occur due to the surface termination of threading dislocations, originating from the low-temperature growth condition during the growth of $p$-GaN top contact layer, is a well known approach.\textsuperscript{3} In other words, the low-temperature growth condition can result in a multitude of pits on the $p$-GaN surface to lessen the reflection of internal light at GaN/air interface and consequently enhance light extraction efficiency. In the following study, we demonstrate another approach aimed to achieve a naturally textured surface in the GaN-based LEDs. The growth-interruption step and CP\textsubscript{2}Mg surface treatment techniques were simultaneously used in the experiment. The experimental process led to the subsequent formation of dense truncated micropyramids on the surface $p$-GaN top contact layer. The discussion below focuses on electrical and optical properties of the fabricated LEDs.
Samples used in this study were all grown on c-face (0001) 2 in. sapphire substrates in a vertical metalorganic chemical vapor deposition (MOCVD) system. Detailed MOCVD growth conditions can be found in other relevant sources. During the growth, trimethylaluminum, trimethylgallium (TMGa), trimethylindium and ammonia (NH₃) were used as aluminum, gallium, indium, and nitrogen sources, respectively. Biscyclopentadienyl magnesium (CP₂Mg) and disilane (Si₂H₆) were used as the p- and n-type dopants, respectively. The LED structure consisted of a 30-nm-thick GaN nucleation layer grown at 550 °C, a 4-μm-thick Si-doped n-GaN layer grown at 1060 °C, a ten-pair InₓGaₓN/GaN multiple quantum well (MQW) structure grown at 770 °C, a 50-nm-thick Mg-doped p-AlₓGa₁₋ₓN electron blocking layer grown at 1050 °C, and a 0.15-μm-thick Mg-doped p-GaN cladding layer also grown at 1050 °C. After the growth of these layers, a growth-interruption step was performed to interrupt the growth of the initial p-GaN cladding layer. The growth-interruption step was made to stop the supply of TMGa and lasted ~5 min. At the same time, the CP₂Mg flow was supplied for a short period of time (~5 min) to create an Mg-terminated GaN surface. A second p-GaN cladding (contact) layer was then grown again after the Mg-terminated GaN surface was formed. Finally, a heavily Si-doped short-period superlattice (SPS) structure was grown on the p-GaN contact layer to improve the ohmic contact of p-electrode. For the ten-pair InGaN/GaN MQW active region, each pair consisted of a 3-nm-thick In₀.₂₇Ga₀.₇₃N/GaN well layer and a 17-nm-thick GaN barrier layer. For comparative analysis, samples without the aforementioned growth-interruption step were also prepared. Hereafter, the LEDs without and with the growth-interruption step were labeled as LED I and LED II, respectively. For device process procedures, wafers were partially etched until the n-type GaN layer was exposed. Indium tin oxide was subsequently evaporated onto the SPS layers to serve as the p-electrodes. Ti/Al-based contacts were then deposited onto the exposed n-type GaN layer to serve as the n-type electrodes. Finally, Ti/Au (50 nm/1.5 μm) bilayer metals were disposed on the p-electrodes and the n-electrodes to serve as bonding pads. The processed wafers were then thinned down to 90 μm for chipping. The dimensions of the LED dies used in this study were 350 μm × 350 μm. The output power of the bare-chip LEDs was measured by a calibrated integral sphere.

Figures 1(a) and 1(b) show the typical top-view scanning-electron microscopy (SEM) images of samples grown with and without the growth-interruption step, respectively. As shown in Fig. 1(a), the surface morphology of the LED I is near featureless. In contrast, the LED II exhibited a multitude of truncated micropyramids on the surface, as shown in Fig. 1(b). Following is the speculative description of the possible growth mechanism of the truncated micropyramids. During the growth-interruption step, only TMGa was switched off, and other growth conditions were retained. Such treatment may provide an inert surface for Mg atom adhesion caused by the filled dangling bonds on the surface of the initial p-GaN layer and thereby enhance the subsequent growth of the truncated micropyramids. Thus the three-dimensional growth of subsequent p-GaN microcrystals on the Mg-treatment surface occurred predominantly before the islands expanded laterally. As a result, a multitude of truncated micropyramids on the p-GaN layer could be achieved through the application of Mg-treatment process. In the growth of self-assembled microcrystal systems, most of the growth methods are related to the Stranski–Krasanov (SK) mode. Unlike the SK mode, Mg-treatment approach does not require the formation of a wetting layer. In other words, the Mg dissolved from CP₂Mg might be a surfactant that can be used to change the surface free energy of substrate (initial p-GaN layer). For example, As, Sb, or Sn, have been introduced onto the Si/Ge substrate surface to suppress island formation by modifying surface free energies. In this study, CP₂Mg was introduced as a surfactant in order to enhance three-dimensional growth, which is contrary to the suppression occurring in the Ge/Si system using some foreign atoms. By introducing the CP₂Mg precursor to the substrate surface (initial p-GaN layer), the surface free energy may be increased and thereby three-dimensional growth of subsequent p-GaN microcrystals can be enhanced. Additionally, the microcrystal size distribution can be controlled by annealing at different temperatures during the growth-interruption step or by increasing/decreasing subsequent growth time. However, the exact roles of CP₂Mg are still unknown, and therefore a detailed study, including surface chemistry, needs to be carried out to clarify the formation mechanism.

For a conventional GaN-based LED, the vast majority of light emitted from an isotropic source incident on a GaN/air interface will undergo total internal reflection or Fresnel reflection, passing a small amount of the light through the GaN/air interface into air. It is a well-known fact that the escape probability of photons emitting from a textured semiconductor surface is higher than that of a smooth semiconductor surface. Figure 2 shows the typical EQE-current characteristics of LED I and LED II with a bare-chip form. With a 20 mA current injection, the typical output power of LED I and LED II was measured around 6 and 10 mW, respectively, when the LED chips were bonded on the TO 66 without resin encapsulation. It should be noted that all LEDs had an emission wavelength of around 465 nm when a dc current of 20 mA was applied. The EQE was around 11.25% and 18.75% for LED I and LED II, respectively, as shown in Fig 2. Thus, we can enhance the EQE by at least 60% by utilizing the Mg-treatment process. The enhancement of EQE in LED II can be attributed to the multitude of truncated micropyramids on the surface resulting in reduction of the reabsorption probability of the photons due to the fact that the photon path length is shorter before the photons escape into the free space. In other words, the escape cone of emitted photons in LED II would be larger than that...
of LED I. The research assumptions can be indirectly supported by the measurements of beam patterns of studied LEDs. As shown in Fig. 3, the typical beam patterns of LED I and LED II were determined at a dc driving current of 20 mA. It is clear that LED II displayed a narrower beam pattern. This is due to the fact that the photon path length is shorter in LED II before the photons escape into the free space. In other words, the most of generated photons were extracted from the top surface. In LED I, if photons are not absorbed by active layer after undergoing multiple reflections between GaN/sapphire and GaN/air interfaces, they will be extracted from the periphery of LED. That is, the percentage of photons extracted from the periphery of LED I would be higher than that of LED II. As a result, the wider beam patterns were observed in LED I. However, it should be noted that photons undergoing multiple reflections in LEDs would result in the higher absorption probability by active layer and hence the reduction of EQE.

On the other hand, with a driving current of 20 mA, the forward voltages of LED I and LED II were 3.1 and 3.25 V, respectively. To understand the effect of surface morphology on device series resistance, dynamic resistances of the LEDs were also evaluated. For these two LEDs, experimental results revealed that the series resistance was about 10 and 15 Ω for LED I and LED II, respectively. The slightly higher forward voltage of the LED II may be related to the formation of the high-resistivity thin Mg$_x$N$_y$ layer between the initial p-GaN layer and the second p-GaN contact layer. It is an acknowledged fact that high series resistance in LED can cause a severe heating effect, giving rise to the carrier leakage from the InGaN active region especially under high current operation. The heating effect will accelerate the degradation of electrodes and thereby influence the device reliability. According to the preliminary results of life tests, no significant difference between LED I and LED II could be observed. It should be noted that these LEDs were driven by a 20 mA injection current at room temperature during the burn-in tests. To further clarify whether the growth interrupt process will result in a significant degradation or not, burn-in tests performed at high temperature (80 °C) and high driving current (50 mA) are under way and results will be published elsewhere.

In summary, the research has demonstrated electrical and optical properties of GaN-based LEDs with the naturally textured surface formed by application of a growth-interruption step and Mg-treatment processes. Experimental results indicated that GaN-based LED with truncated micropyramids on the surface exhibited a ~60% enhancement in output power. The enhancement can be attributed to the reduction of the photon extraction path length made possible by rough LED surface. We should also note that the typical 20 mA driven forward voltage is only 0.15 V higher than that of conventional LEDs (without the Mg-treatment process).

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Figure captions:

FIG. 2. External quantum efficiency as a function of injection current for InGaN/GaN LEDs without (LED I) and with Mg-treatment process (LED II).

FIG. 3. Typical beam patterns taken from LED I and LED II. These LEDs were all bonded on the TO 66.