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Brightness enhancement of ITO/GaN LEDs by self-aligned micro-net structures

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Arrays of square and hexagonal holes of various dimensions were patterned on indium-tin-oxide (ITO)/GaN light-emitting diodes (LEDs) using the self-aligned method to increase the light extraction area and shorten the optical paths. The hole region was etched to give the sidewall of the active layer a sloped profile, and it was passivated by SiO_xN_y films to extract more light. The self-aligned micro-net LED is at least 10% brighter than the conventional structure in the normal direction without loss of operating voltage or leakage current. The ratio of luminescence to total output power is increased by 25% at a current density of 100 A/cm^2. Moreover, varying the hole dimensions and the designed density increased the peak external quantum efficiency by 5% at a current of 3 mA. The greater axial luminescence and the higher external quantum efficiency make LEDs self-aligned micro-net structures quite useful in surface-mounting and low-power-consuming devices, such as cellular phones.

1 Introduction Group III-nitride semiconductors have recently attracted much attention for solid-state lighting applications [1, 2]. Increasing the external quantum efficiency is very important in fabricating high-brightness GaN-based light-emitting diodes (LEDs). In contrast to p-type GaAs or InP semiconductors, the low concentration of holes limits the conductivity of p-type GaN semiconductor. Top-emitting LEDs depend on a conductive film deposited on the p-GaN layer to spread the current uniformly. This conductive layer should not only form an ohmic contact with p-GaN but also be transparent to light emitted from the active layer. Ni/Au films are often used as semi-transparent current spreading layers because they exhibit good contact characteristics with p-GaN. However, Sheu *et al.* [3] showed that the transmittance of Ni/Au films is only 60% to 80% at wavelengths of 450-550 nm. The conventional Ni/Au contacts can be replaced with more transparent conductive materials to reduce the absorption of the current spreading layers and thus increase the external quantum efficiency of LEDs. Numerous studies [4–7] have addressed the application of indium-tin-oxide (ITO) to GaN-based LEDs. The transmittance of ITO films exceeds 85% in the visible spectrum region, and LEDs with ITO contacts are now commercially available. Several works [8–10] have discussed improving the light extracted from LEDs using micron-scale structures. Choi *et al.* [9, 10] demonstrated that the sidewalls in micro-LEDs were important in the extraction of light from the mesa structure. A higher ratio of the total surface-area, including the top and sidewall areas, to the light-emission-area is desired, because then more pathways are available by which the generated photons can escape. However, LEDs with ITO contacts are normally encapsulated by epoxy materials after packaging and the refractive index of ITO (n_r=1.9) differs from

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that of epoxy material (n_r=1.5). SiO_xN_y (n_r=1.67) passivation can be introduced to act as an optical medium to reduce the reflection at the interface because its refractive index is just between that of ITO and epoxy materials. In this article, ITO is applied to the micro-LEDs with SiO_xN_y passivation and the process is simplified by self-aligned method to increase the light extraction area and shorten the optical paths.

2 Experiment The InGaN–GaN multi-quantum-wells (MQWs) LED wafers were grown on c-face sapphire substrates by a metal-organic chemical vapor deposition (MOCVD) system. The epitaxial structure comprised 4-μm-thick n-GaN, a 0.1-μm-thick InGaN–GaN (MQWs) active layer, and 0.1-μm-thick p-GaN. Additionally, the carrier concentrations of the p-GaN and n-GaN were 5×10^{17} cm^{-3} and 3×10^{18} cm^{-3}, respectively. A wafer with a peak wavelength at 465 nm was cleaned in H_2SO_4 and NH_4OH solutions to remove organic contaminants and native oxides. The simplified self-alignment process was performed as depicted schematically in Fig. 1. The ITO (280 nm) and SiO_2 (400 nm) films were initially deposited on p-GaN by e-beam evaporation and plasma enhanced chemical vapor deposition (PECVD) systems. Arrays of square- and hexagonal-hole of various dimensions were patterned on the SiO_2/ITO/GaN structure. After SiO_2 was reactively etched with CHF_3/O_2 plasma, the photoresist was removed by O_2 plasma and ITO/GaN was subsequently reactively etched using inductively coupled Cl_2/Ar plasma. After a micro-net structure was formed, the samples were immersed in buffered oxide etch (BOE) solution to remove the SiO_2 mask and then annealed at 500°C in the nitrogen ambient to produce ohmic contacts. Cr/Au (0.08 μm/0.8 μm) metallization was employed for the n-type contact layer, and the p- and n- bonding pads. The samples were passivated with SiO_xN_y (210 nm) film by PECVD. Reactive gases, SiH_4, N_2O, NH_3 and N_2, were supplied inside the reactor chamber and their flow rates were 5, 20, 20 and 355 sccm. The temperature, pressure and RF power during deposition were 250 °C, 500 mTorr and 100 W. The refractive index of SiO_xN_y films was measured by N&K Analyzer, and the value was 1.67 at a wavelength of 470 nm. After the front-end process had been completed, the samples were polished, scribed and diced into chips. Finally, each kind of chip with its own micro-net structure was packaged into TO-Can forms. An IS CAS-140B system integrated with a Keithley 2430 source meter was used to measure the current-voltage and current-power characteristics of these LEDs. The luminescence was obtained in conformity with CIE (International Commission on Illumination) specifications, and the total power was measured by collecting all directional light inside an integrated sphere.

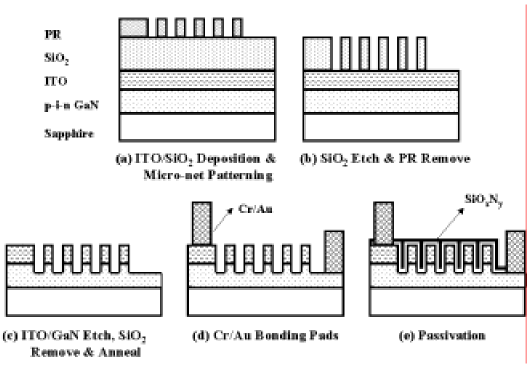

Fig. 1 Process flow diagram: (a) ITO/SiO_2 deposition and lithographic patterning, (b) etching SiO_2 and removing the photoresist, (c) etching ITO/GaN, removing SiO_2 and annealing, (d) Cr/Au metallization, (e) SiO_xN_y passivation.

3 Results and discussion Figure 2 plots the forward current-voltage characteristics of the micro-net LEDs with arrays of square and hexagonal holes with 5 and 10-μm-dimensions. The LED with the conventional structure exhibits a forward voltage of 3.2 V and a micro-net structure of 3.3 V when a 20-mA-current is injected. The forward voltage of the micro-net LEDs may have been slightly higher because of the additional contact resistance resulted from the reduction in effective ohmic contact area of ITO with p-GaN.

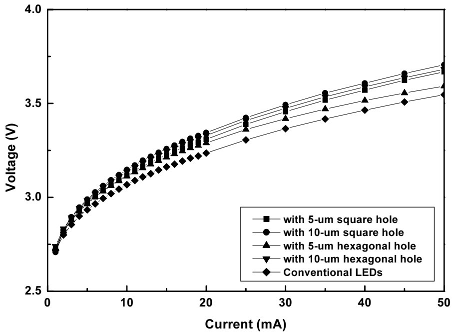

Fig. 2 Measured forward voltage as a function of the injected currents of GaN-based LEDs with self-aligned micro-net and conventional structures.

Figure 3a) plots the current-luminescence and current-power relationships of LEDs. When a 20mA-current is injected, the LEDs with the micro-net structures have a similar output power but a 10% better normal luminescence than the conventional LEDs. Figure 3b) also plots the ratio of normal luminescence to output power of the LEDs with different structures versus the injected currents. The ratio represents the concentration of the extracted light in the axial direction. Notably, the LEDs with arrays of 5-μm hexagonal holes structure reveal a 25% higher ratio at a 50-mA current, which is equivalent to a current density of 100 A/cm^2, than the conventional ones. It might be attributed to the larger sidewall area provided by the micro-net structure and thus increase the scattering probability of the photons extracted through the sidewalls in the axial direction. Therefore, more extracted light from micro-net LEDs would normally propagate than that from conventional LEDs. Table 1 summarizes the electrical and optical characteristics of the micro-net and the conventional LEDs. When the LEDs with various structures were negatively biased at 5 V, the devices exhibited almost the same leakage level.

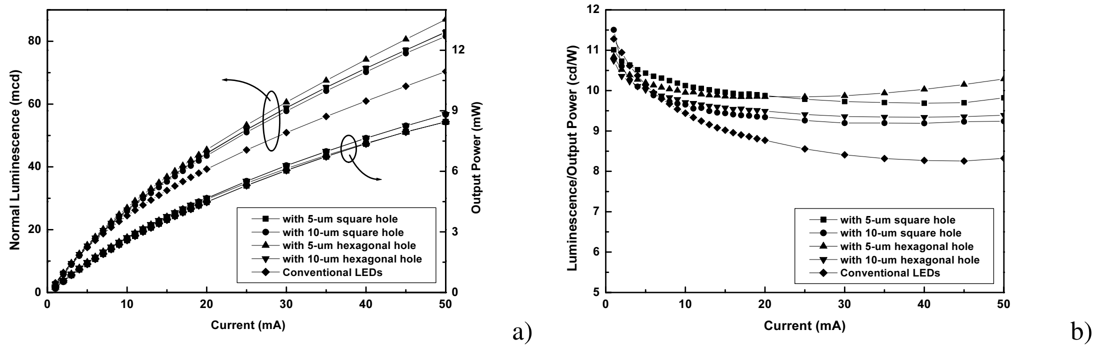

Fig. 3 a) Normal luminescence and output power b) Ratios of normal luminescence to output power as functions of the injected currents of GaN-based LEDs with self-aligned micro-net and conventional structures.

Table 1 Comparative data for LEDs with various structures (Forward and reverse characteristics of LEDs obtained with a 20-mA injection current and a –5 V bias).

Shape of Holes	Dimension (μm)	Forward Voltage (V)	Luminescence (mcd)	Output Power (mW)	L/PO (cd/W)	Reverse Current (μA)
Square	5	3.31	44.2	4.48	9.9	0.56
Square	10	3.34	43.5	4.66	9.3	0.46
Hexagon	5	3.29	45.5	4.62	9.8	0.49
Hexagon	10	3.33	44.4	4.67	9.5	0.54
Conventional	None	3.24	39.3	4.48	8.8	0.54

Figure 4 plots the relationship between the external quantum efficiency and the driving current. The external quantum efficiency of LEDs with micro-net structures exceeds that of the conventional LEDs by approximately 5%. The dimensions and the density of the holes can be varied to maximize external quantum efficiency of the LEDs at an operating current of 3 mA. This structure is quite useful for increasing the output power at low current.

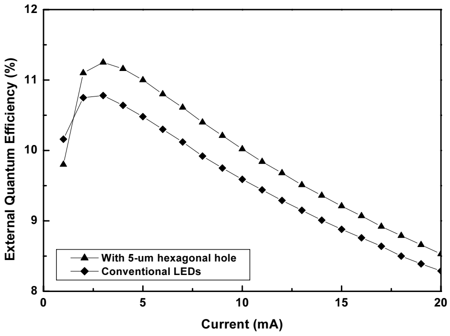

Fig. 4 External quantum efficiency as a function of the injection currents of GaN-based LEDs with self-aligned micro-net and conventional structures.

4 Summary This article proposes a feasible method for fabricating micro-LEDs with ITO contact. The self-aligned micro-net LEDs are a least 10% brighter than the conventional structure in the normal direction without loss of operating voltage and leakage current. The ratio of luminescence to total output power is increased by 25% at a current density of 100 A/cm^2. Additionally, the peak value of external quantum efficiency can be increased by 5% by varying the dimensions and the density of the holes at a low current of 3 mA. With higher normal luminescence and external quantum efficiency, LEDs with such a structure are quite useful in surface-mounting and low-power-consuming devices.

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