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Enhancement of the light output performance for GaN-based light-emitting diodes by bottom pillar structure

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For the demand of having higher light output power at a lower power consumption, the conventional GaN-based LED chips fabricated on the sapphire substrate still could not achieve such a requirement because of having a relatively low value of the external quantum efficiency (η_{ext}). The main reason for such a low efficiency value is resulted by the great extent of the total internal reflection (TIR) happened at the interface of GaN/air. It thus limits the extraction efficiency to about $1/4n^2$ (about 4%) in the GaN semiconductor slab. Consequently, structural design and fabrication technology of LEDs for higher light extraction was emerged as great interests.

Several approaches have been reported to improve the above mentioned situation. By using truncated inverted pyramid geometry, the mean photon path-length within the crystal is decreased to reduce the effects of internal loss mechanisms. Through the photonic crystals and random surface texturing designs could allow light to be escaped more easily. However these structural modifications for the light extraction improvements are mainly focused on the top of LED chips. Whereas, by reducing the light escape from the substrate could also help a LED to improve its light output power to a certain extent. For example, such as patterned sapphire substrate (PSS) has been proposed for this purpose. The original aim of PSS is for reducing the threading dislocations (TDs) densities during the growth of GaN epilayer. Because of reducing the TDs in the GaN microstructure, PSS could results in improving the internal quantum efficiency. In addition, it has been proved that a PSS could cause the scattering light intensity associated with its surface roughness which directly improves the light output power of the LED in a certain extent. In this work, a theoretical model to study the influence of light output intensity by the substrate with geometric patterns design (bottom pillar (BP) substrate) was proposed to achieve an optimal design for light extraction of a GaN LED. Furthermore, the experimental works were also conducted as for comparing the theoretical results.

In the following theoretical calculations, a three-dimensional model based on the finite-difference and time-domain (FDTD) on solving the Maxwell's equations with periodic boundary condition introduced by the two-dimensional hexagonal array of the bottom pillar structure was employed to calculate the light field intensity distributed inside the LED. Such a device structure is simply shown in Fig. 1. The sapphire substrate has a two-dimensional hexagonal pillar structure. The average distance between neighboring hexagonal pillars is=1.75 μm to 2.75 μm.

In fabricating a LED as for easy comparing with the theoretical results, the sapphire substrate was etched by inductively coupled plasma (ICP) dry etching to form an array of hexagonal patterns of BP structure with a standard photolithography process. The etching depth for bottom pillar structure was controlled by about 3500 Å to 4500 Å. After fabricating the BP structure, the GaN LED was grown on the etched sapphire by MOCVD as shown in Fig 1.

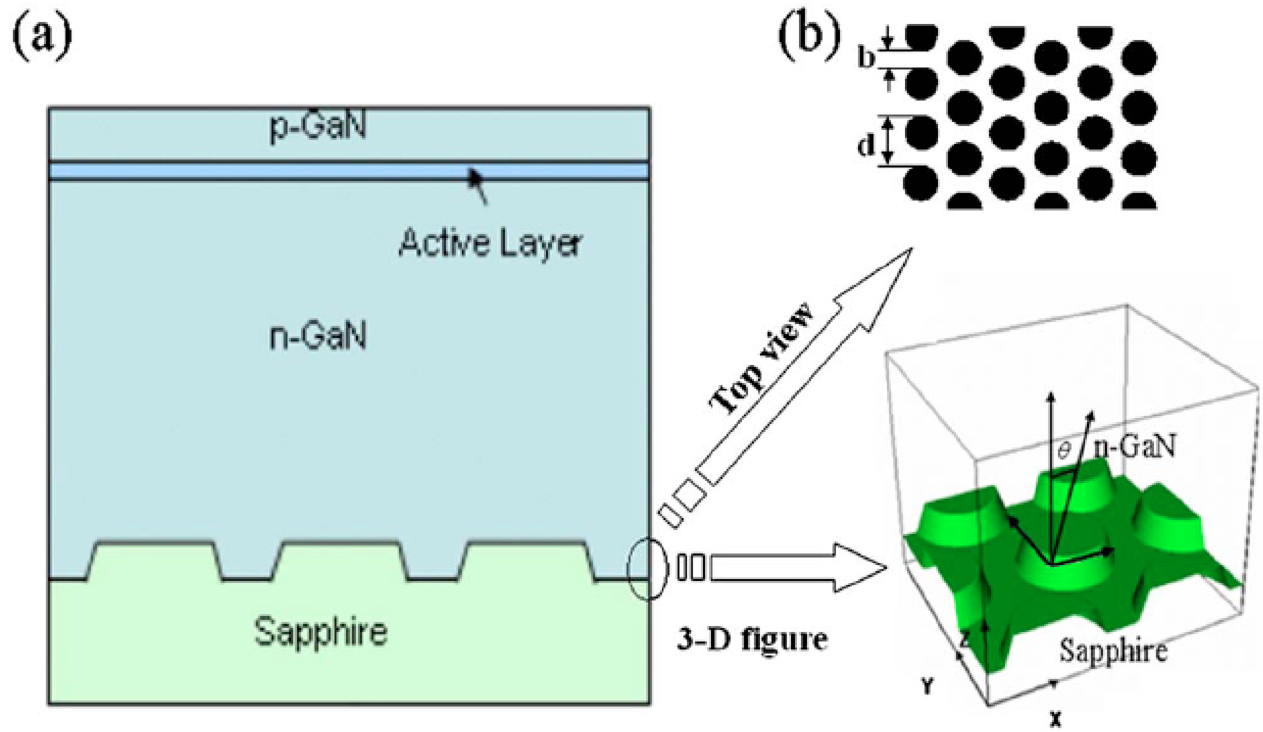

Fig1. Illustration for the GaN LED with bottom pillar structure

As clearly revealed in Fig. 2, the sapphire etched with a pillar structure on its surface has a sidewall angle 111.9°. Additionally, the top side diameter and the height of the pillar are with 1378.1 nm and 356.3 nm, respectively.

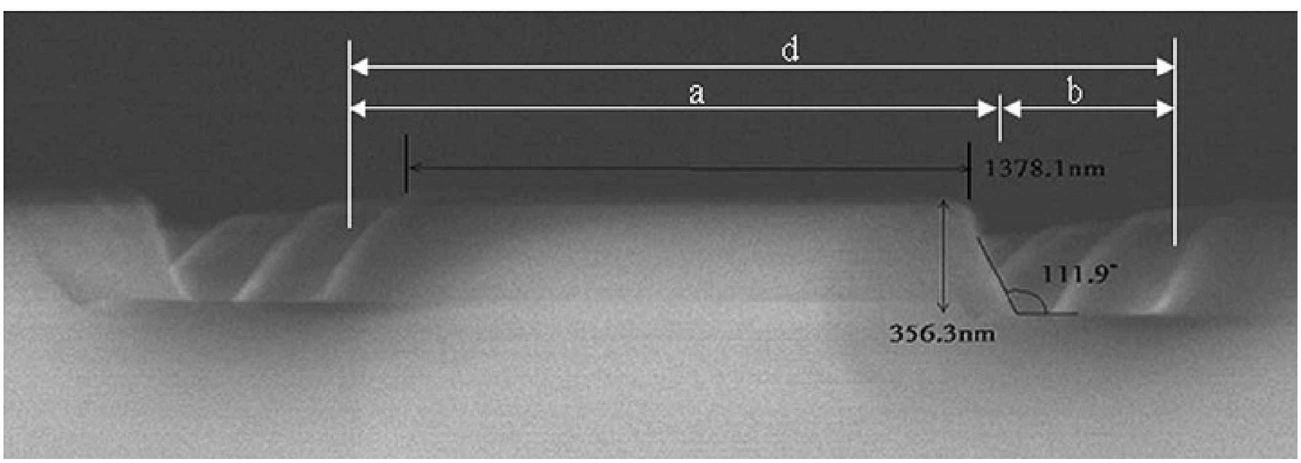

Fig2. SEM image of etching profile of the bottom pillar on the sapphire substrate.

For theoretical calculations, the average value of 0.45 μ m obtained in the experiment were adopted for the depth of the bottom pillar structure in order to analyze the influence of bottom pillar structure on the light output intensity. The diameter of the pillar is assigned as **a**, the spacing of the pillar is **b**, and the pitch of the pillars is **d** with **d=a+b**. With a fix value of 1.5 μ m for the diameter of the pillar, the value of spacing **b** is intentionally adjusted from 0.25 μ m to 1.25 μ m in the following calculations. The normalized light intensity illustrated in Fig. 3 is evaluated by comparing the light power of LED with BP structure to that of LED without BP structure. The LED has a peak value of about 30% enhancement at the ratio of d/b = 3. The result is happened at the condition of the spacing b just equal to a half of the diameter a. Obviously, the bottom pillar structure could enhance the light extraction of LEDs. The above simulation results could be qualitative explained by means of the double-slit model. Based on this model, the light intensity is expressed as:

$$I = 4A_0^2 \frac{\sin^2 \beta}{\beta^2} \cos^2 \gamma \qquad (1)$$

where $\beta = \frac{\pi}{\lambda} b \sin \theta$ and $\gamma = \frac{\pi}{\lambda} d \sin \theta$

I is the light field intensity, A_0 is the amplitude, b is the slit width, d is the separation of the slits. For the pillar structure, parameters of b and d are directly corresponding to the spacing and the pitch of pillars as shown in Fig. 2. The angle θ in equation (1) corresponds to the angle between the vertical z axis and the direction of the diffracted light by bottom pillar structure as illustrated in Fig. 1(b). As predicted by this equation, the factor $(\sin^2\beta)/\beta^2$ is corresponding to the width b of a slit that means the spacing of pillar and the term $\cos^2\gamma$ is the characteristic of the interference pattern. The product result of $(\sin^2\beta)/\beta^2 \cos^2\gamma$ is the central maximum of a slit which acts as an envelope of the interference pattern. The effect of decreasing b causes the full width at half maximum (FWHM) of the envelope mainly concentrates on the location relative to the 0th and results in the strongest light intensity only happened for this order. Furthermore, through the reflection induced by the scattering of the BP structure, a large amount of light power could be reflected back to the top side of a LED which could then enhance the light power output from the top side of the device. Therefore an initial decrease of the spacing of pillar b favors the enhancement of light power output of the LED. An optimum normalization value or a peak value of light power extraction is then obtained. After this peak value, a further decrease of b has reached to such a value that it makes the term of $(\sin^2\beta)/\beta^2$ approximately equal to 1, the light intensity is then strongly dominated by the interference term of $\cos^2\gamma$. Under this situation, the number of interference slits per unit phase angle now increases with further decrease of b. The light intensity allocating to the 0^{th} should be relatively diminished with an increase of the d/b (because of an increase in the number of interference slits). The overall result causes the light reflection induced by the scattering of the BP structure to be reduced to a great extent. Thus the light power vertically reflected back to the top side of a LED should be diminished with a further decrease of b.

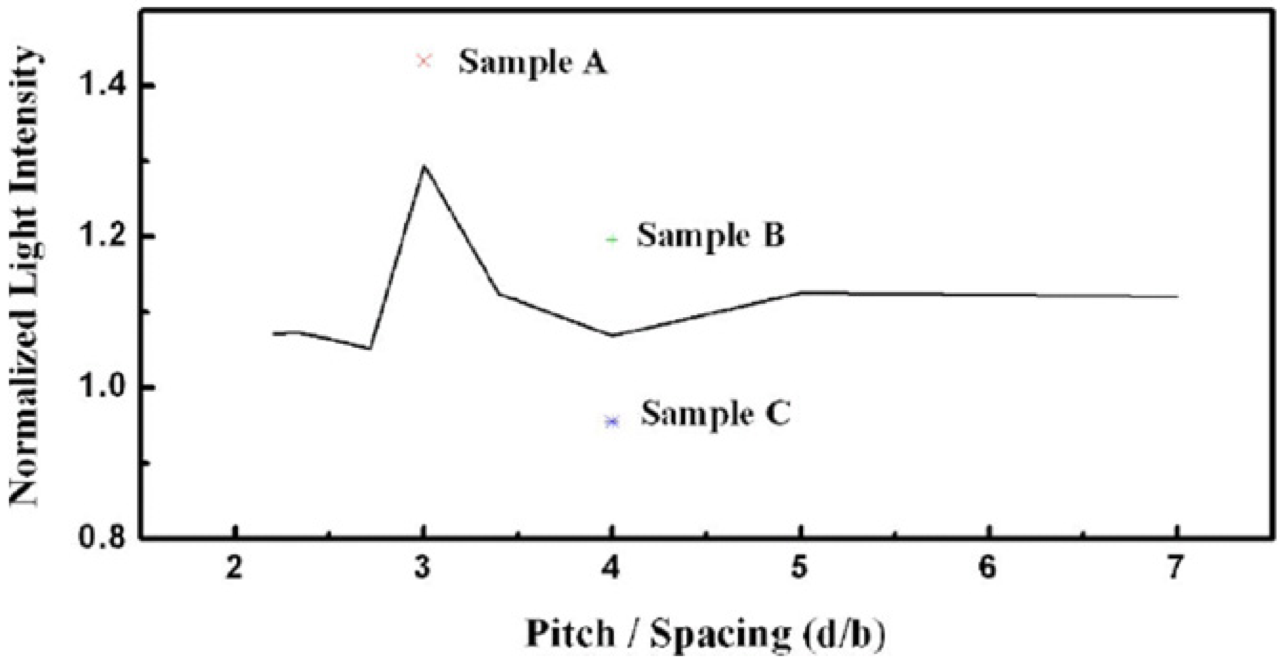

Fig3. The enhancement factor as a function of pitch to spacing ratio.

To compare with the simulated results, three set of samples A , B, and C were fabricated with the pitch to spacing ratios (d/b, length measured in nm) as 3 (d/b =1.5/0.5), 4 (d/b=2/0.5), and 4 (d/b=4/1), respectively. The normalized light output intensity measurements of these samples are also shown in Fig. 3. Since the central wavelength of the LED without BP structure is located at 450nm, the light output intensities of the samples with BP structure are all normalized to that of the LED without BP structure at 450nm as for comparisons. Focusing on the samples A (with d/b ratio 3) and B (with d/b ratio 4), sample A has a better improvement than the sample B with showing the same trend to the theoretical calculations. Under the same d/b ratio as 4 for samples B and C, the sample B has a higher normalization value about 24% than the sample C which reveals the fact that the sample B has better light output intensity than the sample C. It implies that the BP structure designed for the sample C conversely makes it have lower light output intensity than the device without BP structure. Obviously, the sample C is intentionally fabricated with a 2 times spacing larger than the sample B. This result could be well explained by the periodic distribution of BP structure. Under the limit of same size for a LED, an increase of both the diameter of the pillar and the spacing results in a decrease of the number of BP. This directly diminishes the probability of light diffraction mechanism caused by the BP structure. Therefore, a decrease of BP density on the sapphire substrate directly reduces the light reflection by the light scattering of the BP structure.