Polarization-Dependent Sidewall Light Diffraction of LEDs Surrounded by Nanorod Arrays

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***Abstract*—The polarization behavior of the light-emitting diodes (LEDs) with nanorods surrounding the p-mesa is investigated. The nanorods were fabricated using a natural nanosphere lithography and are intended to diffract laterally propagated light. In the horizontal direction, s-polarized light is dominated since the injected carriers choose to fill up the lowest energy state in a direction parallel to the quantum-well layers. The p/s-polarized ratio starts to increase with the increase of radiated angles and eventually saturates. Since the Bragg diffraction of laterally propagated p-polarized mode by nanorods is more efficient than the s-polarized light, the p/s-ratio of the device with nanorods is higher than that without rods. The p/s-ratio of the LED with nanorods is 1.96 at 90°, and is 1.52 when the integrating intensity between 0° and 90° is considered.**

***Index Terms*—Diffraction, light-emitting diodes (LEDs), nanorods, polarization.**

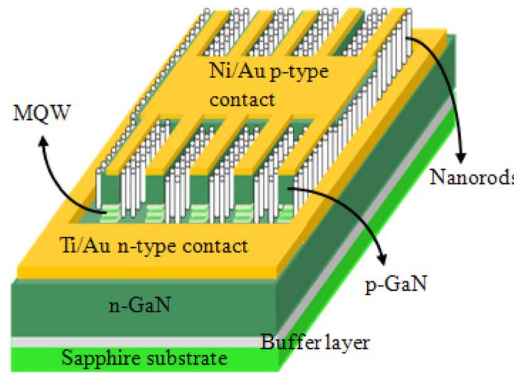

Fig. 1. Illustration of the device profile of an LED encompassed with nanorod arrays.

I. Introduction

As GaN-based light-emitting diodes (LEDs) have become widely used in flat-panel displays, one emerging task in reducing the cost of the panels is by adopting a polarized light source so that the polarizer between the backlight module and liquid crystal is not needed. Therefore, the study of polarized LEDs has attracted much interest. A straight-forward approach to achieve the polarized light is to define nano-scale patterns on the chip surface, thus filtering out the undesired polarization or converting it to a certain polarization direction. Partially polarized output of green LEDs on a c-plane substrate was demonstrated by coupling surface plasmons in the one-dimensional Ag grating structure [1]. Also, polarization behaviors have been observed from photonic crystal LEDs in different lattice directions [2]. Furthermore, polarized results were shown from LEDs packaged with backside reflectors that collect sidewall emission [3]. There are also reports that focus on the epitaxial properties, GaN-based material in particular, that lead to polarized light emission [4]–[6]. Generally, a quantum-confined Stark effect is observed for InGaN grown on the c-plane sapphire substrate. It alters the valence band structures and thus results in a nonpolar light emission. On the other hand, nonpolar- and semipolar-oriented nitride materials have enabled partially polarized light output. Therefore, polarized LEDs have been demonstrated using m-plane or a-plane sapphire substrates [7], [8].

In this work, we investigated the polarization behaviors of laterally propagated light diffraction from nanorods surrounding the light-emitting mesa. We used a nanorod fabrication technology similar to our previous reported work on the enhancement of light output from LEDs encompassed with nanorods [9]. With a proper design of the light-emitting pattern, a polarized light output is demonstrated. The nanorod acts as the grating structure in the vertical direction, which possesses the property of polarization selectivity.

II. Devices Fabrication

The sample was grown on a sapphire substrate by metal–organic chemical vapor deposition (MOCVD) with an epi-structure consisting of a 3-μm n-type GaN layer, 12 periods of InGaN–GaN multiple quantum-well (MQW) layers, and a 0.16-μm Mg-doped p-type GaN layer. The device fabrication starts from depositing a p-type Ni–Au (12 nm/150 nm) contact, which also functions as an etch mask for the subsequent inductively coupled plasma reactive ion etching (ICP-RIE) etching for p-mesa definition. As illustrated in Fig. 1, the probe contact pad on p-type is $100 \times 100\ \mu m^2$ with five $10 \times 100\ \mu m^2$ fingers (10 μm away from each other) extended in both directions. Such a device structure blocks light emission from the surface area and is aiming on obtaining more accurate angular profiles in both s-polarized [transverse electric (TE)] and p-polarized [transverse magnetic (TM)] directions of sidewall emission from the longer mesa edges, thus mitigating interference and

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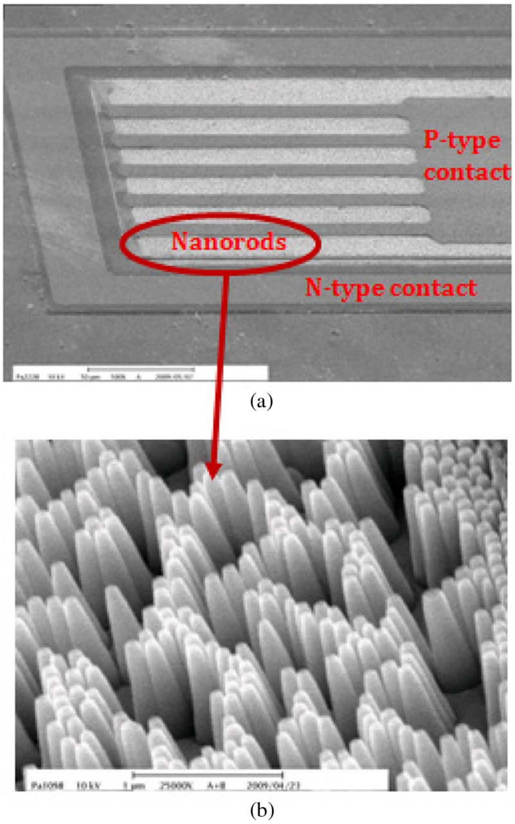


Fig. 2. (a) Top view image of the LED with nanorods and (b) close-up view of the nanorods.

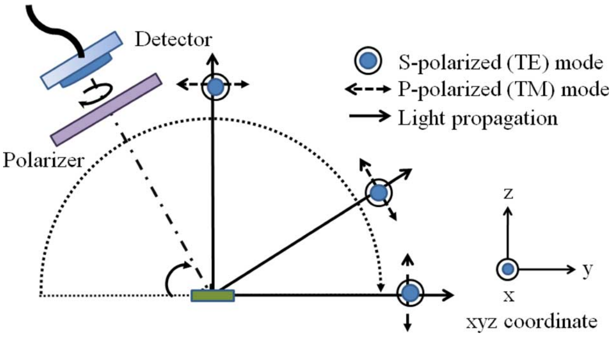
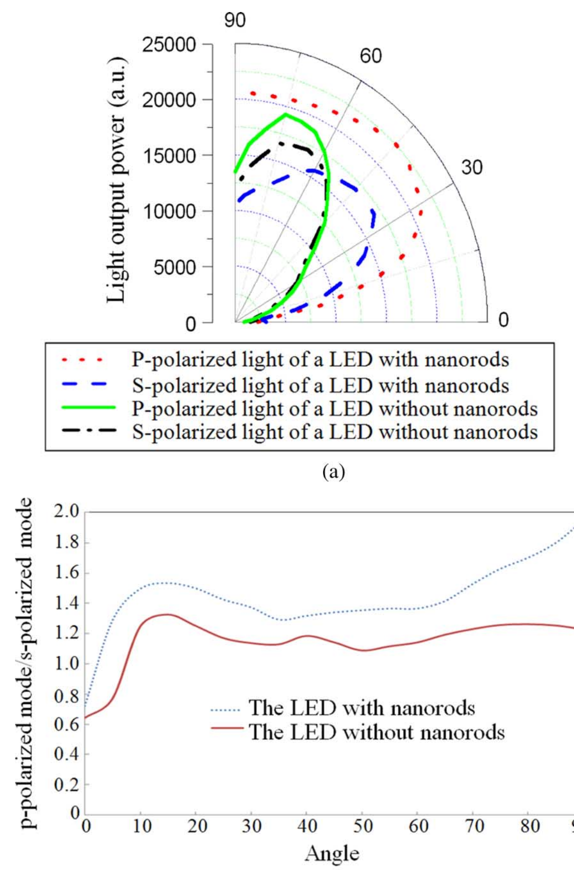


Fig. 3. Experimental setup for angular dependent polarized light measurement. Directions of p- and s-polarized light and the xyz coordinate are also indicated.



(b)

Fig. 4. (a) Radiation profiles of the devices with and without nanorods biased at an injection current 1 mA. (b) The p/s-polarized ratios at various radiated angles.

polarization compensation of optical radiation from the short edges. We then spin-coated a monolayer of 100-nm-diameter self-assembled silica spheres on the sample as the etch mask. This procedure enables a subsequent ICP-RIE dry etching process to etch through the p-GaN and MQW layers and to create a nanorod array 400 nm in depth and 100 nm in diameter. The 10-μm-wide nanorod array is closely adjacent to the p-mesa with a fill factor 0.2 (see the scanning electron microscopic images in Fig. 2). Next, Ti–Au (12 nm/120 nm) was deposited on the n-GaN to serve as the n-type contact pad.

III. Results and Discussion

The radiation profiles were extracted using the experimental setup shown in Fig. 3. The optical power detector was attached to a rotating arm situated 15 cm away from the sample stage. A commercial polarizer with 99.98% polarizing efficiency was inserted in the optical detection path so that s- and p-polarized modes can be extracted. In the experiment, the radiated angle at the surface normal direction of the sample is defined as 90° and the rotating plane is perpendicular to the longer part of p-mesa. The directions for s-polarized (TE) and p-polarized (TM) modes are illustrated in Fig. 3.

The radiation profiles of both s- and p-polarized modes biased at an injection current of 1 mA are demonstrated in Fig. 4(a) along with the corresponding p/s-polarized ratio shown in Fig. 4(b). For comparison purposes, the device with the same fabrication process but without nanoparticle coating, i.e., a device with the same mesa pattern but without nanorods, is also characterized. Basically, for the LED without nanorods, the shadow of the metal mesa induces multiple internal reflections in the LED chip and the light intensity is eventually extracted toward the surface normal through sidewall scattering. On the other hand, for the device with nanorods, the extracted light from the mesa is directly interacted with the adjacent nanorods. As compared with the LED without nanorods, the polarization behavior can be clearly seen for the device with rods. The polarized ratio at various radiated angles can be analyzed as follows. For the c-plane InGaN–GaN MQW, the lowest $|x\rangle$-liked and $|y\rangle$-liked valence bands are degenerated, while the $|z\rangle$-liked state is split to a higher energy state (see Fig. 3 for the xyz coordinates). The carriers are injected by first filling the $|x+iy\rangle$ state and the emitted light will be polarized in the x- and y-directions. Therefore, light emission at 0° along the y-axis is mainly polarized in the x-direction. Moreover, since a thick metal layer is coated on top of the light-emitting mesa and the generated photons in the active layer are radiated from the sidewall through multiple reflection in the epi-structure, the $|y\rangle$ polarized light is further reinforced.

For the LED without nanorods, since the surface of p-mesa is covered by a thick metal layer, the generated photons are extracted to the air through mesa sidewall scattering. When the radiated intensity above 0° is extracted, $|y\rangle$-liked state starts to contribute to the p-polarized light and the p/s-ratio is increased with the angle until it peaks up at 15°. The p/s-polarized eventually saturates in the range between 1.1 and 1.2 for most of the radiated angles in the surface normal direction, which is due to the contribution of $|y\rangle$-liked state to the p-polarized light. The dip between roughly 15° and 50° is believed to be associated with the refractive index difference of GaN in different crystal directions. Since the GaN is anisotropic material where the refractive indexes along the c-axis and perpendicular to the c-axis are 2.46 and 2.37, respectively [10], the p-polarized light (which has z-polarized component) and s-polarized light will experiment different refractive indices. Since a higher refractive index leads to the lower light extraction efficiency, the extraction of p-polarized light is affected and p/s-ratio decreases for the angles around $15^\circ \sim 50^\circ$.

As for the device with nanorod array, we find that the p/s-ratios are 1.53 and 1.96 at the 15° and 90° peaks, respectively. And the polarized ratio is 1.52 when the integrating intensity between 0° and 90° is considered. As we know, the interaction between nanorod arrays and laterally propagated light from p-mesa follows the equation, $k_{\rm rad} = k_{//} \pm mG$ where $k_{\rm rad}$ and $k_{//}$ are the wave vector of the radiation mode and the laterally guided mode, respectively, and $G = 2\pi/a$ is the lattice vector of the nanorod array. Since the diffraction efficiency is higher when the incident light is polarized in the direction parallel to the grating grooves [11], 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, making the p/s-ratio of the device with nanorods higher than the one without rods.

IV. Conclusion

We studied the polarization behavior of the devices with nanorods surrounding the light-emitting mesa. At the radiated angle 0°, s-polarized light dominates since the injected carriers choose to fill up the lowest $|x\rangle$ energy state. The p/s-polarized ratio increases with the radiated angle and eventually saturates as the $|y\rangle$ state starts contributing to the p-polarized light. And a dip between 15° and 50° is observed due to the difference of refractive indexes in different crystal directions. For a device with nanorods, the polarized ratio at all radiated angles is larger than that of the device without rods. The p/s-ratio of the LED with nanorods is 1.96 at 90°, and is 1.52 when the integrating intensity between 0° and 90° is considered.

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