Improvement in Light-Output Efficiency of AlGaInP LEDs Fabricated on Stripe Patterned Epitaxy

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***Abstract*—Quaternary AlGaInP light-emitting diodes (LEDs) operating at a wavelength of 630 nm with a stripe-patterned omni-directional reflector (ODR) were fabricated. It is demonstrated that the geometrical shape of stripe-patterned structure improves the light extraction efficiency by increasing the extraction of guided light. The optical and electrical characteristics of stripe-patterned ODR LEDs are presented and compared to typical ODR and distributed Bragg reflector (DBR) LEDs with the same epitaxial structure and emitting wavelength. It is shown that the output power of the stripe-patterned ODR LED exceeds that of the typical ODR and DBR LEDs by a factor of 1.15 and 2 times, respectively, and with an acceptable forward voltage of about 2.2 V.**

***Index Terms*—AlGaInP, light-emitting diode (LED), omni-directional reflector (ODR).**

I. Introduction

FOR THE yellow to red spectral region, the quaternary AlGaInP material system, grown by low-pressure metal–organic chemical vapor deposition (MOCVD), has proven to be the best choice in many applications such as interior and exterior automotive lighting, traffic lights, full-color displays, and all kinds of indoor and outdoor signs [1], [2]. The major issue in quaternary AlGaInP light-emitting diodes (LEDs) design is the poor light extraction out of the chip due to the total internal reflection of light between air (epoxy) and the semiconductor. Approximately $1/(4n^2)$ of light from the active region can escape from the top and bottom of the device [3]. Furthermore, the AlGaInP LEDs are grown on GaAs substrates that are opaque for the emitting wavelengths of this quaternary material. Hence, most of the light radiated from the active region is trapped in the device and is eventually absorbed by the GaAs absorbing substrate. There are many approaches to enhance the light extraction efficiency of quaternary AlGaInP LEDs by overcoming the issues mentioned above. One common method is the insertion of a distributed Bragg reflector (DBR) sandwiched between the absorbing GaAs substrate and LED structure [4], [5]. However, only the radiated light impinging near normal to the DBR can be effectively reflected. As for the oblique angles of radiated light, the DBR becomes transparent and the light is subsequently absorbed by the GaAs substrate. A more significant improvement of the extraction efficiency can be achieved by replaced the GaAs absorbing substrate by a GaP transparent substrate (TS) through a wafer bonding process [6]–[8]. However, the process is costly and complicated. Recently, the AlGaInP quaternary LED employing a high reflectivity, planar, and omni-directional reflector (ODR) [9]–[11] has become a comparable approach to improve the light extraction efficiency compared to the GaP TS LED. This design allows radiated light with any incident angle to be reflected from the ODR to the top surface of the device. Also it offers a cost advantage over the TS technique. Although the radiated light toward the substrate direction with any incident angles can be more effectively reflected to the top surface of the device with an ODR, the light that can escape from the LED structure will still be limited by Snell's law to a small escape cone. In our previous work [12], the stripe-patterned structure can improve the light extraction by specifically controlling the geometric shape of the stripe pattern through inductively coupled plasma (ICP) etching. In this letter, we report on an ODR quaternary AlGaInP LED combined with a stripe-patterned structure for improving light extraction.

II. Device Fabrication

A schematic cross section image of ODR quaternary AlGaInP LED combing with stripe-pattern structure is shown in Fig. 1(a). The LEDs employed in this report were grown by low-pressure MOCVD (Aixtron 2600G) on a nominally (100) plane 15° off toward to the [111] direction n^+-GaAs substrate. The LED structure consisted of a 60-nm Si-doped $n - In_{0.5}Ga_{0.5}P$ ohmic contact layer, 0.6-μm Si-doped $n - Al_{0.5}In_{0.5}P$ cladding layer, a 0.4-μm undoped active layer region of 630-nm emitting wavelength with 25 period $(Al_{0.3}Ga_{0.7})_{0.5}In_{0.5}P–In_{0.5}Ga_{0.5}P$ multiple quantum wells, a 0.5-μm Mg-doped $p - Al_{0.5}In_{0.5}P$ cladding layer, a 5-μm Mg-doped p-GaP window layer, and a 50-nm Mg-doped p^+-GaP ohmic contact layer. The stripe pattern was defined on the GaP layer by the standard photolithography and then subsequently etched with $BCl_3 - HBr$ as the etching gas in an ICP system to form the dimension of 3 μm wide and 2 μm deep and with a period of 6 μm [Fig. 1(b)]. Following, a calculated reflection of about 90% ODR mirror system composed of a 100-nm ITO current spreading layer, a 100-nm Al_2O_3 low index layer, and a 300-nm Al metal layer were deposited layer by layer on the surface of the stripe-patterned GaP by e-beam evaporation. The p-side of the LED structure and Si substrate carrier were then brought into contact

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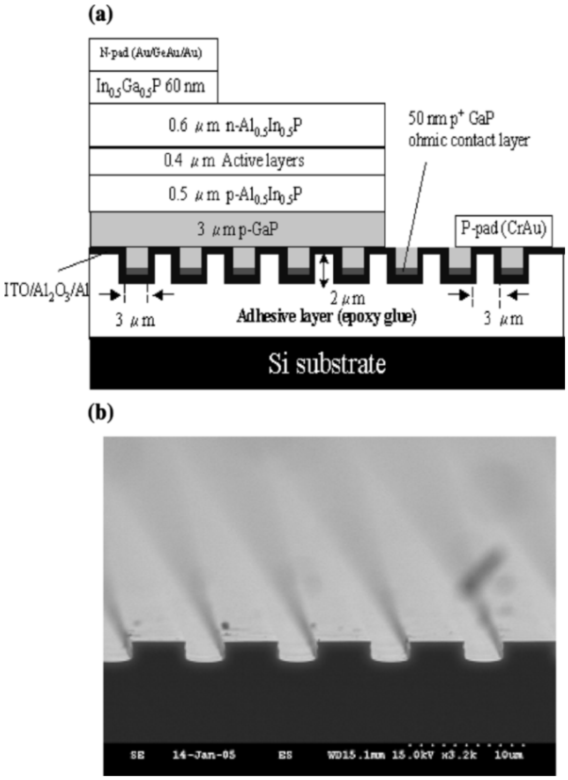

Fig. 1. (a) Schematic of the AlGaInP stripe-patterned LED, and (b) cross-sectional scanning electron micrographs of the stripe-patterned ODR after ICP dry etching.

with the commercially available epoxy glue bonding at the operating temperature of 80 °C. Subsequently, the n-type GaAs substrate was removed by wet chemical etching and the 60-nm Si-doped $n-In_{0.5}Ga_{0.5}P$ ohmic contact layer was partially wet etched to define the n-electrode. The emitting area was then defined by ICP dry etching until the exposure of the ITO current spreading layer. Finally, the Au–GeAu–Au and Cr–Au were deposited as n- and p-electrodes, respectively. Thus, current injected from p-electrode effectively spreads through the ITO current spreading layer into the ridge regions of the GaP layer because only these ridge regions contain a highly doped layer (50-nm Mg-doped p^+-GaP layer) and that makes ohmic contact with the ITO current spreading layer [Fig. 1(a)]. The wafer was then cut into 350 μm × 350 μm chips and packaged into 5-mm lamp for the subsequent measurement (Sample A). The typical ODR LEDs with exactly the same process procedure except without the stripe pattern (Sample B) was prepared for comparison. The conventional LEDs (Sample C) grown on absorbed GaAs substrate with a DBR insertion with the same emitting wavelength as the above two samples were also used as a reference to evaluate the optical and electrical properties of stripe-patterned ODR LEDs. These conventional DBR LEDs had a circular Cr–Au p-contact with a 100-nm ITO current spreading layer and the backside contact was an Au–Ge layer deposited by e-beam evaporation on the n-type GaAs substrate [4]. The typical current–voltage (I–V) measurements were performed using a high current measure unit (KEITHLEY 240). The light output power of the LEDs was measured using an integrated sphere with a calibrated power meter.

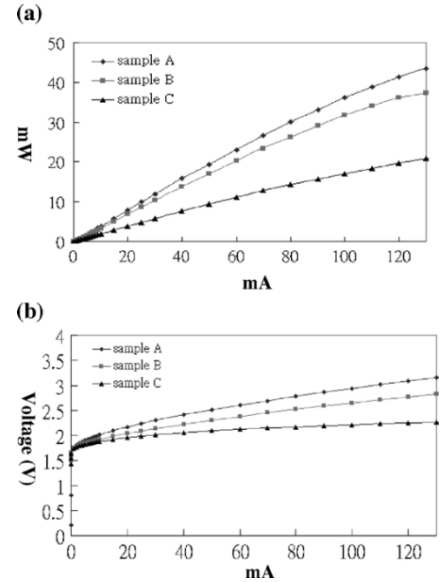

Fig. 2. (a) Output power versus injection current of the stripe-patterned ODR LED (Sample A), the ODR LED (Sample B), and the DBR LED (Sample C). (b) I–V characteristics of Samples A, B, and C.

III. Results and Discussion

Measurements of output power versus injection current of Samples A, B, and C are shown in Fig. 2(a). As can be seen in the figure, the output power of the ODR LED and the stripe-patterned ODR LED are significantly larger than that of the DBR LEDs. The ODR LED with 6.8 mW is 1.8 times brighter compared to that of the DBR LED with 3.8 mW at a driving current of 20 mA. This dramatic improvement in output power can be attribute to the lower power loss of guided light rays [10], [11]. The ODR can reflect the emitted light from the active region with arbitrary angle more effectively than the DBR. Thus, part of the guided light can be extracted by the LED employing the ODR. Although the ODR LED can more effectively reflect the emitting ray, most of these reflect rays are still trapped in the LED due to the small escaping window. Therefore, the improvement of light extraction efficiency of the ODR LED is limited. In Fig. 2(a), the output power of the stripe-patterned ODR LED is 7.8 mW at a driving current of 20 mA. That is about 15% larger than that of the ODR LED, and is coincident with our previous ray-trace simulation result with this dimension of stripe pattern design [12]. The I–V characteristics of Samples A, B, and C are shown in Fig. 2(b). At a current of 20 mA, the forward voltage is about 2.2, 2, and 1.95 V for Samples A, B, and C, respectively. The slightly higher forward voltage of the stripe-patterned ODR LED and the ODR LED could be due to an un-optimized n-contact (Au–GeAu–Au). In Fig. 2(b), the larger forward voltage of the stripe-patterned ODR LED compared to the ODR LED up to 130 mA is due to the reduction of the p-ohmic contact region. For the stripe-patterned ODR LED, about half of the highly doped layer (50-nm Mg-doped p^+-GaP layer) area that makes contact with the ITO current spreading layer is etched away to form the stripe pattern, increasing the contact resistance. To prove the geometric shape of stripe pattern can improve light extraction, micro-photoluminescence (micro-PL) of the stripe-patterned ODR LED has also been measured. Fig. 3(a) shows the experimental setup of the micro-PL system. The micro-PL system consists of a

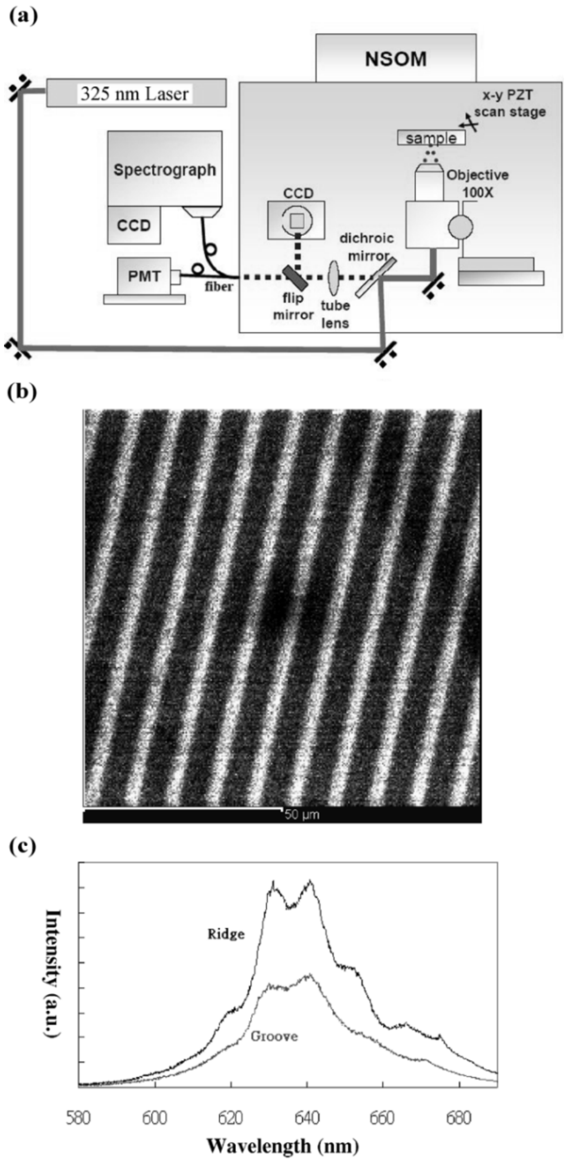

Fig. 3. (a) Experimental setup of micro-PL ($\mu - \mathrm{PL}$), (b) the $\mu - \mathrm{PL}$ mapping image of the stripe-patterned ODR LED, and (c) the $\mu - \mathrm{PL}$ spectra obtained from the ridge region and groove region.

commercial microscope combined with a scanning near-field optical microscope and a confocal microscope. The stripe-patterned ODR LED sample was placed on a piezoelectric transducer (PZT)-controlled stage with a resolution of 2 nm and excited with a 325-nm He-Cd laser through a 100X objective. The focused spot size on the sample was approximately 1 μm in diameter. By moving the PZT stage, the PL spectra of both the ridge and groove regions of the stripe-pattern can be measured under the same excitation density and spot size. The PL emission from the sample was collected with the same 100X objective and fed to a 0.32-m spectrometer with a spectral resolution of 0.1 nm and a cooled ultraviolet-enhanced charged-coupled device. Fig. 3(b) shows the micro-PL mapping image of the stripe-patterned ODR LED under a laser excitation intensity of approximately 30 kW/cm^2. In this figure, the integrated-intensity of the ridge region (bright line) is about 30% larger than that of the groove region (dark line), indicating that the stripe-patterned ODR LED really can increase the light extraction through its geometrical shape that redirects the guided light toward to the top of chip surface. The micro-PL spectra obtained from the ridge and groove regions are also shown in Fig. 3(c). The periodic fluctuation in the PL spectra is caused by the Fabry–Pérot interference between the ODR mirror system and air. In this figure, about a two-times larger PL peak intensity was observed from the ridge region than that from the groove region restating that the employment of the stripe-patterned structure is advantageous to the light extraction.

IV. Conclusion

Highly light-extraction-efficiency AlGaInP LEDs employing a stripe-patterned ODR were fabricated. Their optical and electrical characteristics were measured and compared to a nonpatterned ODR LED and DBR LED. The output power of the stripe-patterned ODR LED at a driving current of 20 mA exceeds that of the typical ODR and DBR LEDs by a factor of 1.15 and 2, respectively, and with an acceptable forward voltage of about 2.2 V. These improvements are attributable to the geometrical shape of stripe-patterned ODR structure that enhances the light extraction efficiency by redirecting the guided light toward to the top exit cone of the LED surface.

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