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Influence of p-GaN annealing on the optical and electrical properties of InGaN/GaN MQW LEDs

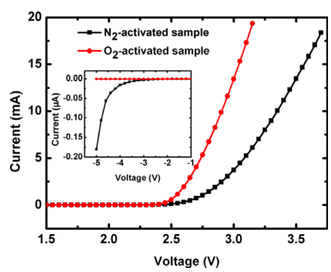
Li Sun [a,b], Guo-En Weng [a,b], Ming-Ming Liang [a,b], Lei-Ying Ying [a,c], Xue-Qin Lv [b], Jiang-Yong Zhang [a,c,*], Bao-Ping Zhang [a,b,c,*]

[a] Laboratory of Micro-Nano Optoelectronics, Department of Physics, Xiamen University, Xiamen 361005, People's Republic of China
[b] Pen-Tung Sah Institute of Micro-Nano Science and Technology, Xiamen University, Xiamen 361005, People's Republic of China
[c] Department of Electronic Engineering, Xiamen University, Xiamen 361005, People's Republic of China

HIGHLIGHTS

- The GaN-based LEDs wafers were annealed in N_2 ambient (800 °C) and O_2 (500 °C) ambient, respectively.
- The N_2 thermal annealing may induce more dislocations in InGaN/GaN MQWs.
- Mg can be further activated during thermal annealing in O_2 ambient.
- The LEDs annealed in O_2 ambient shows better optical and electrical performance.

GRAPHICAL ABSTRACT



The LEDs annealed in O_2 ambient showed a lower forward voltage and reverse leakage currten in comparison with those annealed in N_2 ambient.

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ABSTRACT

Optical and electrical properties of InGaN/GaN multiple quantum wells (MQWs) light emitting diodes (LEDs) annealed in pure O_2 ambient (500 °C) and pure N_2 ambient (800 °C) were systematically investigated. The temperature-dependent photoluminescence measurements showed that high-temperature thermal annealing in N_2 ambient can induce indium clusters in InGaN MQWs. Although the deep traps induced by indium clusters can act as localized centers for carriers, there are many more dislocations out of the trap centers due to high-temperature annealing. As a result, the radiative efficiency of the sample annealed in N_2 ambient was lower than that annealed in O_2 ambient at room temperature. Electrical measurements demonstrated that the LEDs annealed in O_2 ambient were featured by a lower forward voltage and there was an increase of ~41% in wall-plug efficiency at 20 mA in comparison with the LEDs annealed in N_2 ambient. It is thus concluded that activation of the Mg-doped p-GaN layer should be carried out at a low-temperature O_2 ambient so as to obtain LEDs with better performance.

1. Introduction

Group III nitride semiconductors are very important materials for optoelectronic devices such as light emitting diodes and laser diodes [1,2]. The achievement of highly conductive p-type GaN is a

* Corresponding authors at: Laboratory of Micro-Nano Optoelectronics, Department of Physics, Xiamen University, Xiamen 361005, People's Republic of China. Tel.: +86 592 2180149.
E-mail addresses: jyzhang2010@xmu.edu.cn (J.-Y. Zhang), bzhang@xmu.edu.cn (B.-P. Zhang).

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key factor in the fabrication of GaN-based optoelectronic devices. To date, Mg is the commonly used acceptor for p-type GaN. However, the as-grown Mg-doped GaN film is highly resistive because of the formation of the Mg–H complexes via reaction with hydrogen during metalorganic chemical vapor deposition (MOCVD) growth. Recently, several studies have suggested that thermal annealing in N_2 ambient at a temperature of 800 °C can effectively activate the Mg-doped GaN epilayer by dissociating Mg–H complexes and then increase the hole concentration in p-GaN [3]. While other groups have reported that thermal annealing in O_2 ambient at a relatively lower temperature of 500 °C can also achieve highly conductive p-type GaN [4,5], the presence of O_2 during thermal annealing would remove hydrogen that passivated Mg atoms by forming H_2O. T. C. Wen et al. [4] made comparison between the optical and electrical properties of p-GaN annealed in pure O_2 ambient and pure N_2 ambient, respectively. They found that the carrier concentrations of the samples annealed in O_2 ambient were higher than those annealed in N_2 ambient. The high activation efficiency of p-GaN in O_2 ambient is due to the higher activity of oxygen than that of nitrogen. C. H. Kuo et al. [5] reported that the forward voltage and dynamic resistance of the InGaN/GaN LED annealed in pure O_2 ambient at 500 °C were better than that annealed in pure N_2 ambient. P. Ma et al. [6] investigated the electroluminescence intensity of InGaN/GaN quantum wells based on Mg-doped GaN annealed in pure O_2 ambient and pure N_2 ambient, respectively. They found that the electroluminescence intensity was enhanced after O_2 thermal annealing. The enhanced electroluminescence intensity is attributed to the reactivation of Mg acceptor through postgrowth annealing in O_2 ambient, besides the dissociation of Mg–H complexes by forming H_2O. Up to now, comparison of these two kinds of annealing methods has been performed, separately, in p-GaN film, in InGaN/GaN quantum wells and in LEDs. However, few works have been done to compare the effect of the high-temperature annealing in N_2 ambient (800 °C) and the low-temperature annealing in O_2 ambient (500 °C) on the optical properties of the InGaN/GaN quantum wells and the performance of LEDs fabricated using such annealed quantum wells.

In this paper, the as-grown GaN-based LEDs wafer was divided into a few pieces and annealed in pure N_2 ambient and pure O_2 ambient, respectively, and then LEDs were fabricated using these annealed samples. The optical properties of InGaN/GaN quantum wells and the electrical properties of related LEDs were investigated through temperature-dependent photoluminescence (PL), current–voltage (*I*–*V*), and light output power–current (*L*–*I*) measurements. Our results indicated that the low-temperature thermal annealing in O_2 ambient can lead to better optical and electrical properties of InGaN/GaN MQWs LEDs compared with the high-temperature thermal annealing in N_2 ambient. Corresponding reasons are discussed.

2. Experiment

The samples used in this letter were grown on a 2-in diameter (0001)-oriented sapphire substrate, followed by a 30 nm GaN nucleation layer, a 2 μm undoped GaN layer, and a 2 μm n-GaN layer. The active region included ten periods of 2 nm InGaN quantum wells and 18 nm GaN barriers. A 20 nm p-AlGaN electron blocking layer and a 380 nm p-GaN layer were grown on top of the active region. The as-grown samples were annealed for the purpose of generating holes at 800 °C in pure N_2 ambient (N_2-activated sample) for 20 min and at 500 °C in pure O_2 ambient (O_2-activated sample) for 6 min. After annealing, PL spectra were measured as a function of temperature ranging from 15 K to 300 K using a 405 nm line of 13.5 mW cw semiconductor laser. To fabricate the LEDs, 240 nm ITO thin film was subsequently evaporated onto the p-type GaN surface by an electron beam evaporator as a transparent conducting layer. Then mesa patterns of 300 μm × 300 μm were etched by an inductively coupled plasma etching system. Then, a Cr/Au bilayer structure was deposited as n-type and p-type contact electrodes. Finally, the *I*–*V* and *L*–*I* characteristics of LEDs were measured under DC-bias condition at room temperature.

3. Results and discussion

Fig. 1(a) shows the normalized temperature-dependent PL spectra of as-grown, N_2-activated, and O_2-activated samples in the range from 15 K to 300 K. The peak position is given in Fig. 1(b) as a function of temperature for these three samples. It is clearly seen that all the samples show “S shaped” variations. The “S shaped” shift emission has the peak position redshift–blueshift–redshift with increasing temperature. For example, as the temperature increases from 15 K to 30 K, the PL peak of the N_2-activated sample redshifts 7 meV. Subsequently, the PL peak blueshifts 17 meV between 70 K and 220 K. When the temperature is increased above 220 K, the peak position redshifts again. Such an S-shaped behavior is usually attributed to carrier localization which is common in highly inhomogenous semiconductor materials. This phenomenon can be explained as follows [7,8]: at low temperature, the radiative recombination process is dominant and the lifetime of the carrier increases. Carriers are randomly distributed in different localized states. With a rise in temperature, the kinetic energy of carriers increases. Hence, the weakly

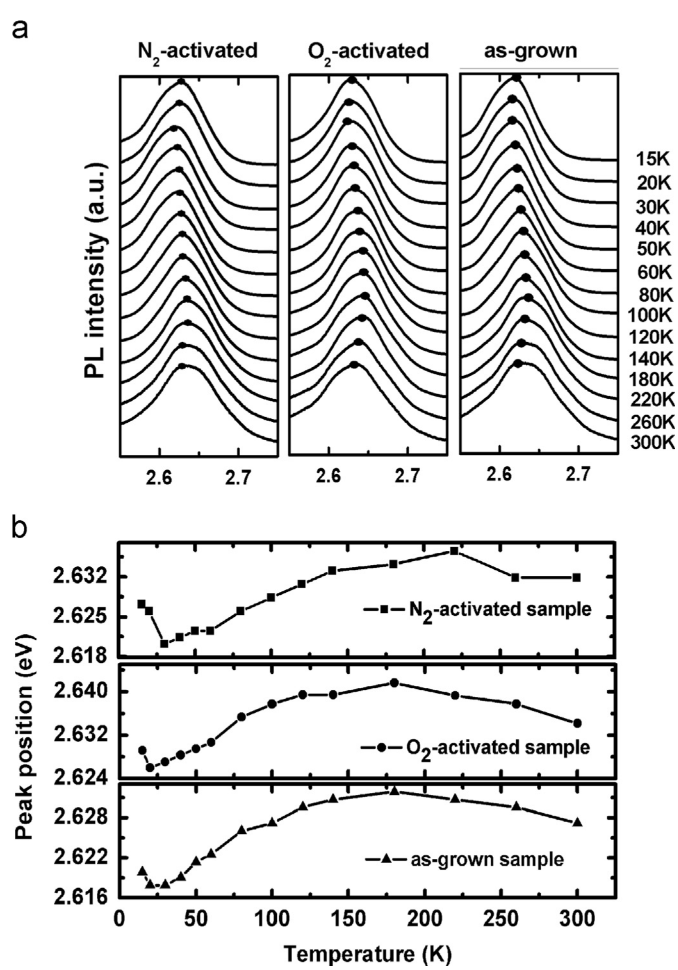

Fig. 1. (a) Temperature-dependent PL spectra and (b) PL spectral peak position as a function of temperature for the N_2-activated, O_2-activated,and as-grown samples.