Hydrogen-Free Epitaxy of Colored LEDs Based on InGaN/GaN MQWs

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High brightness colored LEDs based on InGaN multiple quantum wells have recently been an attractive topic of research to achieve high efficiency photonic devices. In this study, we investigated a 3-period $In_xGa_{1-x}N$/GaN multiple quantum well LED grown on special templates by metal-organic chemical vapor deposition. All epitaxial layers, including the InGaN/GaN multiple quantum well active region, n-GaN and p-GaN were realized using nitrogen alone as a carrier gas. The growth details and device fabrication steps were studied. High resolution X-ray diffraction was used to analyze the thickness of the barrier and well, and composition of indium in the multiple quantum well active region. The Hall effect measurements were used to analyze the electrical properties of the epitaxial layers. Electroluminescence measurements were performed to estimate the optical band-gap of the LED structure.

1. Introduction

Colored GaN-based light emitting diodes (LEDs), particularly using InGaN/GaN multiple quantum wells (MQWs) as active regions, have attracted considerable scientific attention [1]. To improve device performance, significant effort has been exerted in the design and fabrication of such LEDs in terms of enhancing material quality, light-extraction efficiency, and metal–semiconductor ohmic contacts [2].

III-nitride devices are often heteroepitaxially grown on foreign substrates, but there are lattice and coefficient of thermal expansion mismatches between the epitaxial layers and the substrates. These two mismatches cause high dislocation density and high stress in the epilayers during the initial growth and cooling processes [3]. There has thus been a strong motivation to find different substrates and templates to address these problems [4]. In this study, we demonstrate an LED whose active region is based on a 3-period $In_xGa_{1-x}N$/GaN MQW structure. We discuss the growth, fabrication and characterization of the LED in detail. In addition, we discuss the temperature-dependent p-GaN Hall measurements to estimate the activation energies of the Mg acceptors.

2. Experimental procedure

A close-coupled showerhead metal-organic chemical vapor deposition (MOCVD) reactor was used to grow III–N layers on templates consisting of GaN ($\approx 5~\mu m$) on micropatterned sapphires.

Prior to the deposition of the active region, growth started with a ($1~\mu m$) heavily doped n-GaN using SiH_4 at $950\,°C$ and 500 Torr. This was followed by growth of the 3-period MQW structure of $In_xGa_{1-x}N$ quantum wells and Si doped n-GaN barrier layers. Growth temperatures of the InGaN well and GaN barrier
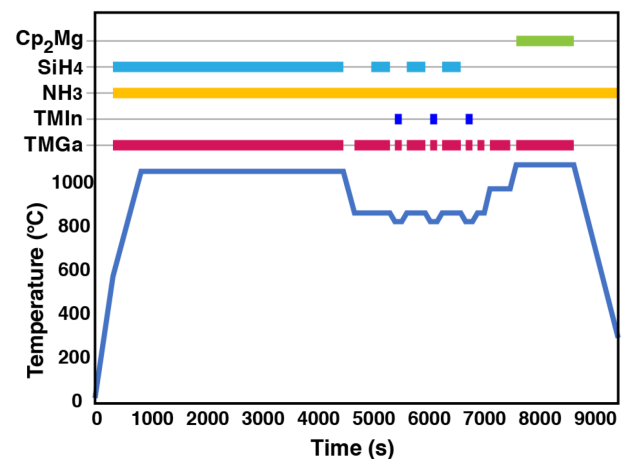

Fig. 1. Schematic of the growth temperature profile and source-switching sequences as a function of growth time for the entire LED structure.

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layers were alternated. Each quantum well was composed of $In_xGa_{1-x}N$ grown at 830 °C with 700 sccm NH_3 flux, 1.0 sccm TMGa flux and 100 sccm TMIn flux. Subsequently, each quantum barrier was composed of n-GaN grown at 870 °C with 700 sccm NH_3 flux and 1.0 sccm TMGa flux. During the active region growth, the reactor pressure was fixed to 500 Torr, as in processes reported in previous studies [5]. Finally, a (250 nm) p-GaN layer using bis(cyclopentadienyl)magnesium (Cp2Mg) was grown at 1090 °C on top of the MQW structure. The growth temperature profile and source-switching sequences of the InGaN/GaN MQW LED structure are displayed in Fig. 1.

3. Results and discussion

To evaluate the structural characteristics of the MQW structure, we performed X-ray θ–2θ measurements on the interfaces between the wells and barriers. The presence of several well-defined satellite peaks in the X-ray diffraction spectrum of the MQW indicate the interfaces between wells and barriers are abrupt [6]. Figure 2 shows the experimental and simulated high resolution X-ray diffraction (HRXRD) rocking curves of the InGaN/GaN MQW LED structure in (002) ω–2θ scan mode. It is seen that the theoretical and experimental curves are in good agreement.
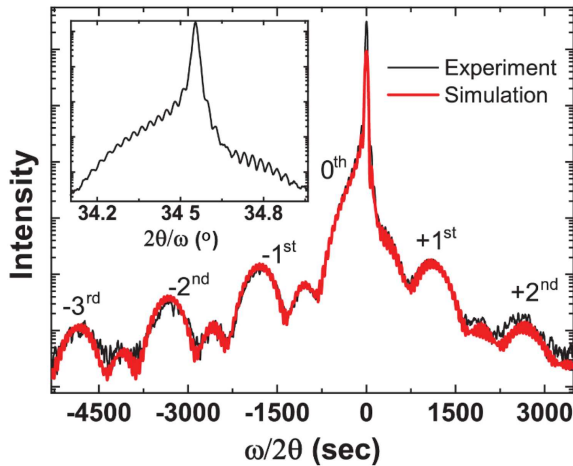

Fig. 2. Experimental and simulated high-resolution XRD rocking curves of the LED structure in (0002) $\omega/2\theta$ scan mode. Inset shows the GaN (002) peak in $2\theta/\omega$ scan mode.

Periodicity of the well and barrier thickness are calculated from the positions of the satellite peaks by

$$L = (\lambda/\Delta\theta)2\cos(\theta_B), \qquad (1)$$

where L is the period (summation of well and barrier thickness), λ is the X-ray wavelength (1.5406 Å), $\Delta\theta$ is the angle difference of two adjacent satellite peaks, and θ_B is the Bragg angle of GaN (002) [7].

Based on XRD analysis, the thickness of the $In_xGa_{1-x}N$ well, GaN barrier and the indium compo-

sition of the LED structure are estimated to be 2.5 nm, 8.5 nm and $x = 14\%$, respectively.

We carried out the van der Pauw–Hall effect measurements, revealing the Mg-doped p-GaN film with a doping level and mobility of around 5.3×10^{17} cm^{-3} and 5.3 cm^2 V^{-1} s^{-1}, respectively, at room temperature. Furthermore, temperature-dependent hole concentration of the p-GaN at temperatures from 300 to 400 K was performed to estimate the activation energies of Mg acceptors. Figure 3 shows the hole concentration of the Mg-doped p-type GaN layer as a function of reciprocal of temperature [8]. The thermal activation energy obtained from the slope of the Arrhenius plot is ≈ 216 meV.
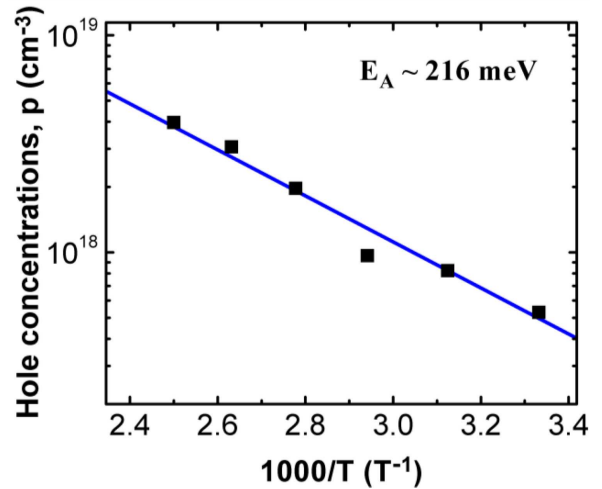

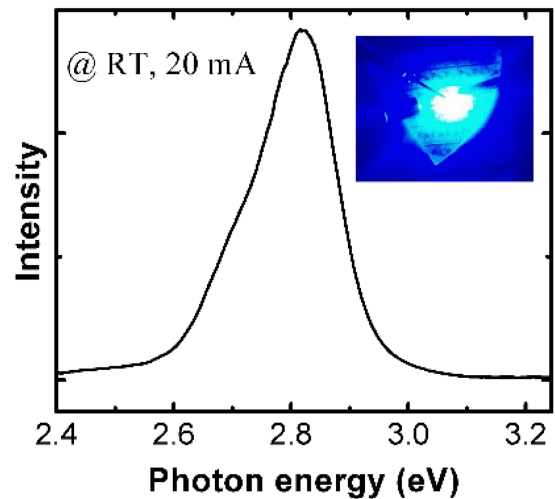Fig. 3. Temperature dependence of the hole concentrations of Mg-doped GaN.

Fig. 4. EL emission spectrum of the LED recorded at 20 mA current at room temperature, and corresponding camera image of the emission (inset).

The LED mesa structures were defined by means of standard fabrication techniques such as photolithography, plasma etching, and lift-off [9]. Ohmic contacts were realized for the n-metal electrode consisting of

Ti/Al/Ti/Au (20/100/20/100 nm) and the *p*-metal electrode consisting of Ni/Au (5/5 nm) on *n*-GaN and *p*-GaN, respectively. Optical characterization of the LED was performed using an optical spectrum analyzer [10]. Electroluminescence emission of the LED was measured at room temperature at a current of 20 mA as seen in Fig. 4. The EL peak is located at around 440 nm (with a photon emission of ≈ 2.82 eV).

4. Conclusion

We demonstrated an LED based on a 3-period InGaN/GaN MQW active region, grown on special templates by MOCVD. Each epitaxial layer in the entire LED structure was grown without using hydrogen carrier gas. Device fabrication details were studied, and HRXRD was used for analysis of the MQWs. XRD results show that the GaN barrier had a thickness of 8.5 nm, and the $In_xGa_{1-x}N$ well had a thickness of 2.5 nm with an In composition of $x = 14\%$. Temperature-dependent Hall measurements were performed to analyze the electrical properties of the *p*-GaN. The thermal activation energy of the Mg acceptors in the *p*-GaN was estimated to be 216 meV. Electroluminescence measurements showed that the LED emits photons at a wavelength of approximately 440 nm.

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