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Effect of residual compressive stress on near-ultraviolet InGaN/GaN multi-quantum well light-emitting diodes

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ABSTRACT

Thinning was investigated to reduce the residual compressive stress in GaN-based near-ultraviolet light-emitting diode (NUV-LED) substrates. This stress has a knock-on effect of reducing piezoelectric fields in the LED structure. As the sapphire substrate thickness is reduced, the compressive stress in the GaN layer is released, resulting in wafer bowing. The wafer bowing-induced mechanical stress alters the piezoelectric fields, which in turn reduces the quantum-confined Stark effect in the InGaN/GaN active region of the LED. The electroluminescence spectral peak wavelength was blue-shifted, and the internal quantum efficiency was improved by about 15% at an injection current of 50 mA. The LED with a 45-μm-thick sapphire substrate exhibited the highest light output power of ∼29 mW at an injection current of 50 mA, an improvement by about 39% compared to that of a 150-μm-thick sapphire substrate without increasing the operating voltage. The simulation results confirm that the relaxation of the compressive strain in the InGaN/GaN MQW structure results in the reduction of the piezoelectric field and improves the overlap of electron and hole wave functions with a corresponding increase in IQE.

1. Introduction

GaN-based ultraviolet (UV) light-emitting diodes (LEDs) are attracting much attention for applications such as chemical and biological detection systems, water and air sterilization, and primary light sources for phosphor-based white LEDs [1–4]. Particularly, GaN-based near-UV LEDs emitting at ∼385 nm are being widely used as efficient excitation sources for organic and inorganic luminescent materials for white-light generation. For example, a UV-emitting GaN LED chip pumping a red–green–blue or a yellow–green–blue phosphor mix results in white light with an excellent color-rendering index and high efficacy by means of mixing complementary colors. Therefore, GaN-based near-UV LEDs with high internal quantum efficiency and light-extraction efficiency are crucial in the development of white LEDs. However, large compressive stress is developed in the InGaN/GaN multi-quantum-wells (MQWs) grown on sapphire substrate due to a large lattice mismatch between the sapphire substrate and InGaN/GaN layers [5,6], and also due to the difference in thermal expansion coefficient between the sapphire substrate and the grown GaN film when the sample is cooled from the growth temperature to room temperature [7–10]. This compressive stress causes charge separation from the polarization fields in the QW, leading to reduction of the electron–hole wave function overlap and radiative recombination. In addition, the existence of spontaneous and piezoelectric polarization fields in InGaN QWs [11,12] leads to a charge separation effect, which in turn impacts both the radiative recombination rate and carrier dynamics in the QWs [13,14]. It is for these reasons that the internal quantum efficiency (IQE) of InGaN QW LEDs decreases significantly.

Recently, several approaches have been proposed to suppress the charge separation issue by employing novel QWs with improved electron–hole wave function overlap, such as nonpolar InGaN QWs [15], staggered InGaN QWs [16,17], InGaN QWs with a δ-AlGaN layer [18], type-II InGaN QWs [19,20], InGaN-delta-InN QWs [21], and triangular QWs [22]. These approaches used various methods to engineer the InGaN QWs in order to obtain structures with large optical matrix elements, which in turn led to significantly improved radiative recombination rate. Another approach based on strain compensation in the InGaN active layer [23–25] has also been proposed to enhance the IQE of LEDs. However, we are confident that to further improve the quantum efficiencies of the GaN-based near-UV LED devices, better knowledge of its strain

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or stress states between the epitaxial layer and substrate is needed. Mechanical stresses are known to considerably influence semiconductor band gaps and the effective masses of electrons and holes. The substrate thickness in GaN-based LEDs plays an important role in the improvement of light extraction efficiency. Therefore, several attempts to study the effect of sapphire-substrate thickness on the curvature and stress have been carried out, including the examination of thick GaN films with different thicknesses by high-resolution X-ray diffraction at different temperatures [26], and engineering the stress in GaN-based LEDs prepared on sapphire substrates with different thicknesses [27].

In this work, theoretical calculation of the dependence of compressive stress developed in a GaN-based LED on the indium composition is studied. We also report on the effect of sapphire substrate thickness on the relation between the curvature and the residual stress in both the GaN film and the substrate, and on the wavelength of the light emitted from the InGaN/GaN MQWs. The optimization of internal quantum efficiency and light output power for GaN-based UV-LEDs is also discussed. In addition, to investigate the effect of strain relaxation in QWs on the IQE of InGaN/GaN MQW structure, the strain in InGaN QWs was changed in simulations by modifying the degree-of-relaxation parameter from zero, meaning that the InGaN layer has the same lattice constant as the underlying layer, to unity, which corresponds to the InGaN layer having its natural unstrained lattice constant.

2. Experimental

Conventional *c*-plane near-UV LEDs were grown on a 430-μm-thick 2-in. c-face (0001) sapphire substrate in a metal–organic chemical vapor deposition (MOCVD) system. The LED structure consisted of a 30-nm-thick GaN nucleation layer grown on a sapphire substrate, followed by the sequential growth of a 2-μm-thick undoped buffer GaN and 3-μm-thick Si-doped n-type GaN. Then, five periods of $In_{0.05}Ga_{0.95}N$/GaN MQW active regions made from a 3-nm-thick undoped InGaN quantum-well (QW) layer and a 12-nm-thick GaN quantum barrier (QB) layer were grown on n-GaN. Finally, a 40-nm-thick p-GaN layer and a 70-nm-thick highly doped p-GaN layer were grown in the normal sequence. After forming the LED structure, the sample was fabricated by a conventional standard process with 240 μm × 600 μm chip dimensions.

After that, the sapphire substrate was thinned to 150, 120, 90, 70, and 45-μm thicknesses using backside lapping and soft polishing, which can minimize thinning-induced damage and other negative effects that might occur on the backside surface. The lapped and polished LED wafers were then carefully cleaned with acetone to remove residual contaminants on both sides of the wafers. We then used a scribe and break method to fabricate GaN-based LED chips. The bending displacement of 30 LED chips was measured using a 3D surface profiler for each thickness, and the median value was considered. The substrate curvature of each thickness was calculated from the bending displacement and the chip dimensions. The relation between the epilayer stress and substrate curvature is given by Stoney's equation [28].

The elastic modulus and the Poisson ratio of the sapphire substrate were set to 345 GPa and 0.25, respectively [24]. The electroluminescence (EL) characteristics were measured for the sample with 150-μm sapphire substrate thickness, and then the wavelength was repeatedly measured after thinning the substrate of the sample to 120, 90, 70, and 45-μm thicknesses on the same LED chips to eliminate the wafer-to-wafer variation. The LED chips were mounted in a surface mounted device (SMD) package. The light output–current–voltage (*L*–*I*–*V*) characteristics of the packaging LEDs were measured using an integrating sphere to collect the light emitted in all directions from the LEDs at room temperature. The internal quantum efficiency (IQE) values were monitored by an Etamax DOSA-IQE measurement system. The external quantum efficiency (EQE) and wall-plug efficiency (WPE) for the GaN-based near-UV LEDs were also evaluated.

The simulation program used in this work was SiLENSe 5.4 (STR, Inc.) [29]. The multi quantum-well (MQW) structure for the simulation analysis consists of a 3000-nm-thick *n* type GaN, 3-nm-thick InGaN QW, a 12-nm-thick GaN barrier, a 20-nm-thick *p*-type AlGaN electron blocking layer, and 100-nm-thick *p*-type GaN. The threading dislocation density of $5 \times 10^8\ cm^{-2}$ is considered in the simulation as the typical value of GaN heterostructures grown on *c*-plane sapphire substrate. The electron and hole mobility were assumed to be $200\ cm^2\ V^{-1}\ s^{-1}$ and $10\ cm^2\ V^{-1}\ s^{-1}$, respectively.

3. Results and discussion

The actual stress relaxation of the InGaN active layer should be monitored. The InGaN active layer is too thin to collect analytical information. Thus, theoretical calculation was performed to estimate the compressive stress values of InGaN/GaN MQW structure with various indium (In) compositions at room temperature. In this calculation, we assumed that a thin InGaN layer is coherently grown on a thick GaN layer along the *c*-plane. The InGaN layer has the same *a*-axis lattice constant as the GaN layer, and it is under biaxial strain perpendicular to the *c*-plane. The equations used in this calculation are referenced from another study [30].

It can be seen that the compressive stress was gradually increased with increasing In composition, as shown in Fig. 1. When the In compositions are 5% (Near-UV-area), 15% (Blue-area), and 25% (Green-area), the compressive stress values along the *c*-axis are ∼3, 8, and 13 GPa, respectively. However, it is impossible to monitor the actual stress relaxation of the InGaN active layer, because the epitaxial structure is too complicated. Instead, we could monitor and calculate the stress values of the n-GaN layer for simple comparison. Fig. 2 shows the dependence of the bowing curvature of sapphire substrates and the corresponding residual mechanical stress in the grown GaN layer depending on the sapphire substrate thickness. The inset shows the chip size and shape. It has been observed that the curvature of the bowing increases and the residual mechanical stress decreases as the sapphire substrate is gradually thinned from 150 to 45-μm. This is because of the release of the residual compressive stress in the GaN layer as the sapphire substrate thins down. This stress is caused by the difference in thermal expansion coefficients between the GaN film

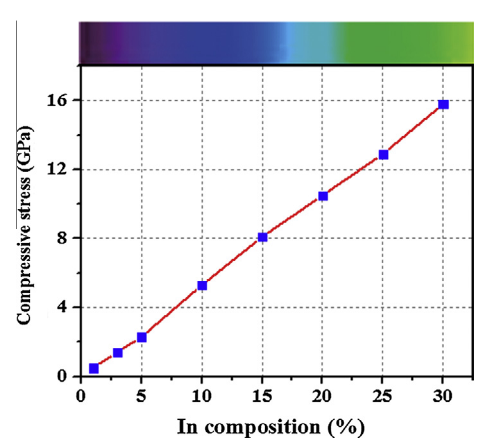

Fig. 1. Calculated compressive stress in strained InGaN layer on GaN layer as a function of In composition.