Strain engineering for the solution of efficiency droop in InGaN/GaN light-emitting diodes

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Abstract: We present a method of increasing light output power and suppressing efficiency droop in vertical-structure InGaN/GaN MQW LEDs without modifying their epitaxial layers. These improvements are achieved by reducing the quantum-confined Stark effect (QCSE) by reducing piezoelectric polarization that results from compressive stress in the GaN epilayer. This compressive stress is relaxed due to the external stress induced by an electro-plated Ni metal substrate. In simulations, the severe band bending in the InGaN quantum well is reduced and subsequently internal quantum efficiency increases as the piezoelectric polarization is reduced.

OCIS codes: (230.3670) Light-emitting diodes; (230.0230) Optical devices.

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1. Introduction

GaN-based light-emitting diodes (LEDs) are potential candidates for next-generation solid-state lighting, because of their long lifetime, small size, high efficiency, and low energy consumption [1,2]. However, conventional InGaN/GaN multi-quantum-well (MQW) LEDs suffer from "efficiency droop" in which the efficiency reaches its peak value at low current density (< 10 A/cm^2) and rapidly decreases with injection current; this phenomenon is a major obstacle to achieving high-power and high-efficiency LEDs for general illumination applications, in which injection currents > 350 mA are employed. Several explanations for efficiency droop have been proposed including Auger recombination [3], electron leakage [4,5], carrier delocalization [6], and lack of hole injection [7].

For the explanation of efficiency droop in InGaN/GaN MQW LEDs, polarization-related effects may be a key factor. Electric fields caused by spontaneous and piezoelectric polarization at the InGaN/GaN heterointerface, lead to the quantum-confined Stark effect (QCSE), resulting in reduction of internal quantum efficiency (IQE) and efficiency droop [8]. To reduce the polarization effects, devices grown on semi-polar and non-polar orientations have been proposed. For LEDs fabricated on the non-polar (1-100) plane (*m*-plane) [9], or the semi-polar (10-1-1) plane (*a*-plane) [10], the efficiency droop is less severe than in LEDs fabricated on the (0001) plane (*c*-plane). It has been also reported that LEDs with polarization-matched AlGaInN or InGaN barriers are shown to have increased light-output power, and reduced efficiency droop due to the decrease of electron leakage [4,5]. All of these methods of averting efficiency droop have done so by modifying the epitaxial layers of LEDs.

Here, we present the first demonstration of the reduced efficiency droop in vertical-structure InGaN/GaN MQW LEDs without modifying the epitaxial layers. It was found that relaxation of interfacial stress at the interface of InGaN/GaN could reduce piezoelectric polarization. Conventional InGaN/GaN MQW LEDs epilayers grown on *c*-plane sapphire substrate have convex curvature due to the high compressive stress caused by the difference in large lattice mismatch and thermal expansion coefficient between the epitaxial layers and the substrate [11]. This results in reduction of IQE [12,13]. However, the vertical-structure LEDs (V-LEDs) fabricated in this work has concave curvature. This concave curvature of the GaN epilayers is due to the external tensile stress [14,15] induced by the electro-plated Ni metal substrate. The external tensile stress could relax the compressive stress in InGaN/GaN MQW LEDs epilayers, reducing the QCSE by reducing piezoelectric polarization. As a result, light output power at high injection current was increased and the efficiency droop was significantly reduced. The blue-shift of peak wavelength in electroluminescence (EL) spectra of V-LEDs indicates enlargement of effective bandgap due to a reduction in the QCSE. In simulations, a declined band in the InGaN quantum well becomes flat and IQE accordingly increases as the compressive strain in the GaN epilayer is relaxed.

2. Methods

A 500-nm-thick undoped GaN buffer layer, a 4-µm-thick *n*-type GaN, an InGaN/GaN MQW active region, a *p*-type AlGaN electron blocking layer, and a *p*-type GaN layer were grown in sequence on *c*-plane sapphire substrates using metal-organic chemical vapor deposition. Vertical-structure LEDs (1 × 1 mm) were fabricated on the substrate. First, active regions were defined by inductively coupled plasma dry etching down to the sapphire substrate, followed by deposition of a 500-nm-thick SiO_2 passivation layer. The Ag-based reflective *p*-type ohmic contact was deposited on the *p*-type GaN, followed by annealing at 400 °C for 2 min in ambient air. Then, a Cr/Au conductive seed layer was deposited on the entire wafer. A 50-µm-thick Ni layer was electroplated as a conductive metal substrate and subsequently the Laser lift-off (LLO) process of the sapphire/MQW LED/Ni structure was performed in air using a Lambda Physik Compex 205 KrF pulsed excimer laser. After LLO, the undoped GaN was etched to expose the *n*-type GaN, followed by the deposition of the Cr/Au *n*-type ohmic contact, forming an *n*-side-up vertical InGaN/GaN LED on the Ni metal substrate.

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The height h of V-LEDs was measured using a Tencor Alpha-Step 500 surface profiler. The curvature of V-LEDs was calculated from the measured height. The optical characteristics of V-LEDs were measured in an unpackaged (on-wafer) configuration using an integration sphere.

The simulation program used in this work was SiLENse 4.1 (STR, inc.) package implementing the 1D model based on the Poisson equation for the electric potential and drift-diffusion transport equations for the electron and hole concentrations [16]. The single-quantum-well (SQW) structure for numerical analysis consists of a 30-nm-thick n-type GaN ([Si] = 3×10^{18} cm^{-3}), 3-nm-thick $In_{0.2}Ga_{0.8}N$ QW, a 12-nm-thick GaN barrier, a 30-nm-thick p-type AlGaN electron blocking layer ([Mg] = 7×10^{19} cm^{-3}), and a 20-nm-thick p-type GaN layer ([Mg] = 5×10^{17} cm^{-3}). The threading dislocation density of 1×10^{9} cm^{-2} is considered in simulation as the typical value of GaN heterostructures grown on c-plane sapphire substrate. The electron and hole mobility were assumed to be 100 $cm^2 \cdot V^{-1} \cdot s^{-1}$ and 10 $cm^2 \cdot V^{-1} \cdot s^{-1}$, respectively.

3. Results and discussion

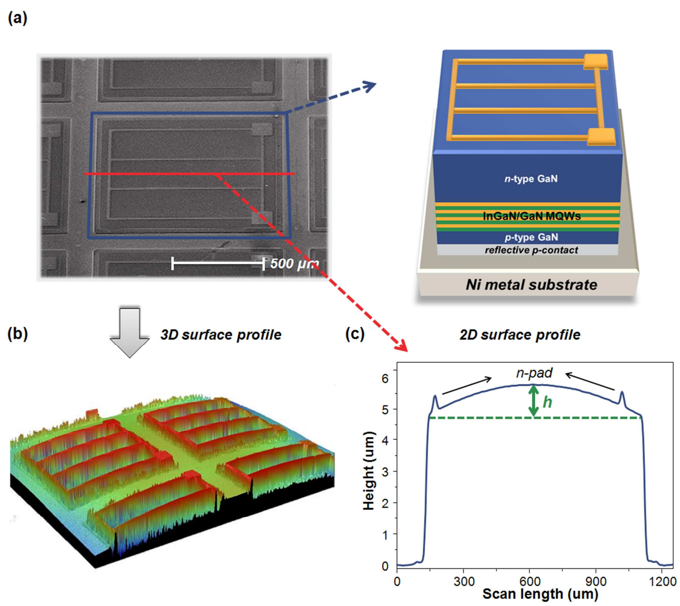

Fig. 1. InGaN/GaN MQW V-LEDs. (a) SEM images and schematic 3D illustration of V-LEDs. (b) 3D surface profile of V-LEDs showing convex curvature in view of n-side up configuration. (c) 2D surface profile of V-LEDs along the solid red line in Fig. 1a.

The n-side up V-LEDs fabricated in this work (Fig. 1a) have convex curvature in the n-side up configuration (Fig. 1b), but in case of p-side up, the curvature is concave, which is opposite to the convex curvature in conventional InGaN/GaN MQW LEDs grown on c-plane sapphire substrate. The convex curvature of V-LEDs is due to the external stress applied by electro-plated Ni metal substrate. The 2-dimensional surface profile of V-LEDs clearly shows convex curvature in view of n-side up configuration (Fig. 1c). The thickness of electro-plated Ni metal substrate with 2-inch diameter gradually increases from edge to center. As a result, the curvature of V-LEDs is not uniform, because the applied stresses to V-LEDs vary according to their position on the Ni substrate.

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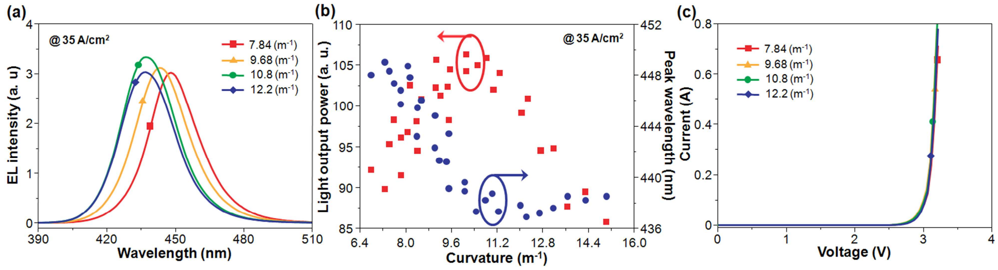

Fig. 2. Light output power and electrical characteristics. (a) EL emission spectra measured at 35 A/cm^2 for V-LEDs with different curvature (values in legend). (b) Measured light output power and peak wavelength of 30 V-LEDs at a current density of 35 A/cm^2 as a function of curvature. (c) Current-voltage (*I-V*) characteristics of V-LEDs with different curvature.

EL spectra (Fig. 2a) were obtained from four V-LEDs with different curvatures at 350 mA injection current (35 A/cm^2). As the curvature of V-LEDs increased to 10.8 m^{-1}, the EL intensity increased and the peak wavelength was blue-shifted. Further increase in curvature caused reduction of EL intensity, but did not blue-shift the peak wavelength. To identify the distribution of light output power and peak wavelength with curvature, the light output power and peak wavelength of 30 V-LED chips at 350 mA were plotted as a function of curvature (Fig. 2b), because sample variations may be the cause the differences in opinion over the origin of efficiency droop [17]. The 30 V-LED chips were located in a small area of 1 × 1 cm in the 2-inch wafer to rule out variations in optical properties of V-LEDs due to the non-uniformity of LED epitaxial layers. As the curvature increased up to 11.0 m^{-1}, the light output power increased and the peak wavelength in the EL spectra was blue-shifted. However, further increase in curvature reduced the light output power and caused a slight red-shift in peak wavelength. The current-voltage (*I-V*) characteristics (Fig. 2c) were obtained for four kinds of V-LEDs with differing curvatures. All V-LEDs show almost the same forward voltage of ~3.02 V at 350 mA. These results show that the optical properties of V-LEDs are mainly affected by the change of curvature in V-LEDs.

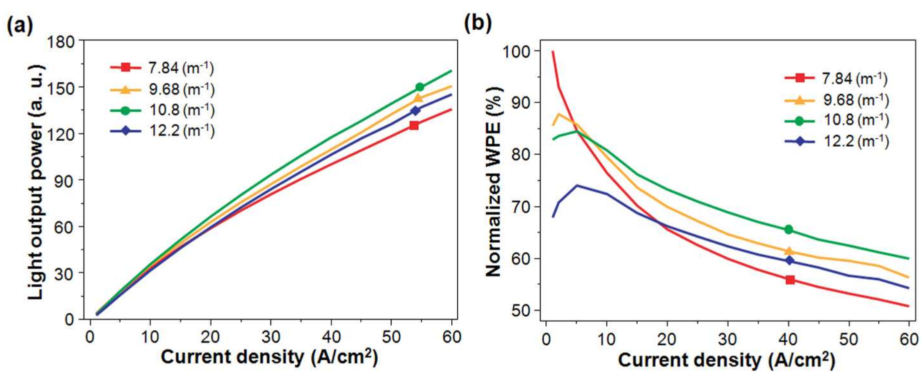

Fig. 3. Efficiency droop behavior of V-LEDs with different curvature. (a) Light output power of V-LEDs with different curvature as a function of current density. (b) Normalized wall-plug efficiency of V-LEDs with different curvature as a function of current density.

In V-LEDs with different curvatures, the light output power increased with the current density, but at a decreasing rate (Fig. 3a). The output power at a high current density (> 10 A/cm^2) increased by 18% as the curvature increased from 7.8 m^{-1} to 10.8 m^{-1}. Further increase in the curvature resulted in the reduction of output power. Normalized wall-plug efficiency (WPE) of V-LEDs with different curvatures was calculated by dividing the measured light output power by the power consumption $P = I \times V$, and normalized to the peak WPE. The efficiency droop was significantly reduced as the curvature of V-LEDs increased (Fig. 3b). Furthermore, the current density for attaining maximum WPE increased and the

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efficiency peak was less sharp as the curvature increased such as the LEDs fabricated on non-polar/semi-polar plane or polarization-matched epitaxial layers as previously reported [4,5,9,10]. This phenomenon could be attributed to a shortening of nonradiative recombination lifetime, resulting in the decrease of WPE a higher current density is required to attain a maximum WPE as well as a suppression of efficiency droop [5,9].

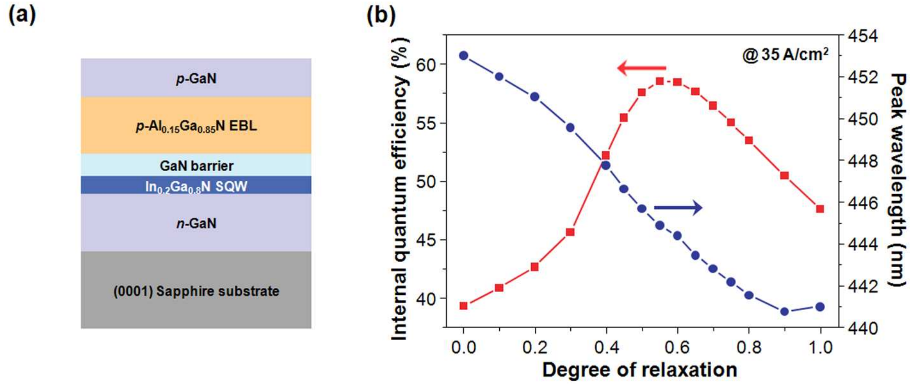

Fig. 4. Simulation of InGaN/GaN SQW. (a) Single quantum well (SQW) structure for numerical analysis. (b) Calculated internal quantum efficiency and peak wavelength for InGaN/GaN SQW structure as a function of 'degree of relaxation'.

To investigate why changing curvatures affect efficiency droop in V-LEDs, numerical analysis of an InGaN/GaN single-quantum-well SQW structure (Fig. 4a) was performed in SiLENSe 4.1. We changed the piezoelectric polarization in InGaN QWs by varying the parameter 'degree of relaxation' from 0 (i.e., InGaN QW with piezoelectric polarization) to 1 (i.e., InGaN QW without piezoelectric polarization). Changes of internal quantum efficiency (IQE) and peak wavelength with the degree of relaxation, were determined by simulation of the InGaN/GaN SQW at a current density of 35 A/cm^2 (Fig. 4b); both of these changes agree well with the change in light output power and peak wavelength determined from the V-LEDs results (Fig. 2b). The IQE and light output power increased by about 20% when degree of relaxation changed from 0.33 to 0.6 and the curvature of V-LEDs changed from 6.8 m^{-1} to 10.2 m^{-1}. This provides the evidence that the changes of light output power in V-LEDs with curvature are due to the changes of IQE. These results show that the changes of light output power and efficiency droop result from the relaxation of piezoelectric polarization in InGaN/GaN QWs.

Energy band diagrams (Fig. 5a) and the wave functions (Fig. 5b) were calculated for both electron and hole in InGaN/GaN SQW structures with different value of degree of relaxation. The energy band diagram is was calculated at a current density of 35 A/cm^2. When degree of relaxation is 0, severe band bending occurred, i.e., the bottom of the quantum well declined. Due to the QCSE, the electron and hole wave functions separate partially, resulting in the reduction of radiative recombination and IQE. When degree of relaxation is 0.55, the band bending was reduced. Therefore, the overlap of electron and hole wave functions and the probability of radiative recombination are simultaneously increased, resulting in the increase of IQE from 39.3% to 58.5% (Fig. 4b). Increasing degree of relaxation to 1 further recovers the band bending, leading to the increase of overlap of the electron and hole wave functions. However the IQE was decreased to 47.7% and this could be due to the drastic decrease of hole concentration in InGaN/GaN SQW (Fig. 5c), resulting in the reduction of electron-hole pair in spite of the increase of electron concentration in InGaN/GaN SQW. Finally, the blue-shift of peak wavelength in experimental and simulated results could be attributed to the increase of effective bandgap due to the decrease in piezoelectric polarization (Fig. 5a).

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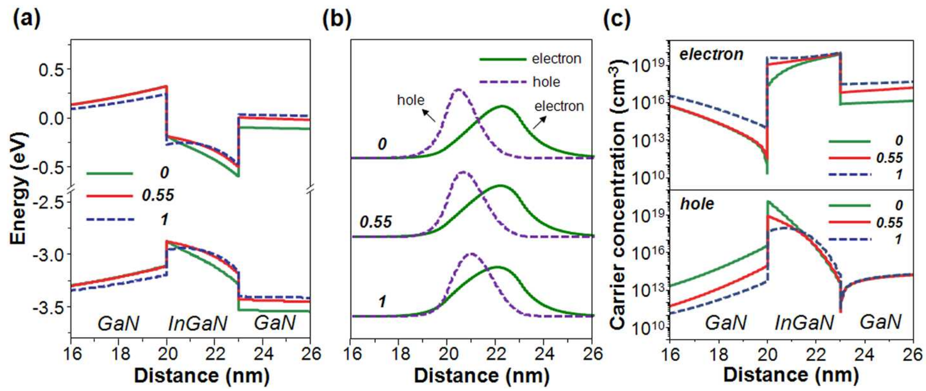

Fig. 5. (a) Calculated band diagram of InGaN/GaN SQW structure at a current density of 35 A/cm^2 with various 'degree of relaxation'. (b) Calculated electron and hole wave functions of InGaN/GaN SQW structure with various 'degree of relaxation'. (c) Electron and hole concentration in InGaN/GaN SQW structure with various 'degree of relaxation'.

4. Conclusions

We demonstrate the suppression of efficiency droop in vertical-structure InGaN/GaN MQW LEDs by relaxing compressive stress. The relaxation of compressive stress in GaN epilayers reduces the piezoelectric polarization, which in turn reduces the QCSE. Therefore, the light output power at a high current density is increased and the efficiency droop is significantly suppressed. Optimizing external stress in V-LEDs by changing their curvatures may allow control of the built-in piezoelectric polarization and reduction of the QCSE to suppress efficiency droop and thereby to improve their light output power.

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