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The properties of reversed polarization yellow InGaN-GaN MQWs in p-side down structure grown by metal–organic chemical vapor deposition on sapphire substrate

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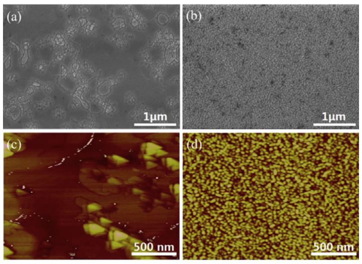
HIGHLIGHTS

- PDMQWs and NDMQWs were investigated and compared systematically.
- Rough p-GaN promotes the formation of In-rich nanodot-like structure in PDMQWs.
- PDMQWs present longer emission wavelength with an extra emission peak from nanodot-like structures.
- Mg memory effect cause Mg residual and the incorporation of C, H, and O impurities in PDMQWs.

GRAPHICAL ABSTRACT

Graphical abstract shows the surface morphology of NDMQWs and PDMQWs. It clearly shows that the rough surface of p-GaN underlying layer can promote the formation of InGaN nanodot-like structure.



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ABSTRACT

The reversed polarization yellow emission InGaN/GaN multiple quantum wells (MQWs) in p-side down (PDMQWs) and n-side down (NDMQWs) structures were grown by metal–organic chemical vapor deposition on sapphire substrates. The properties of PDMQWs in surface morphology, interface quality, optical characteristic, and impurities distribution were investigated and compared with those of NDMQWs. Though degrading the interface abruptness of PDMQWs, the rough surface of p-GaN underlying layer was found to promote InGaN compositional fluctuation or phase separation and the resultant formation of nanodot-like structures with higher In-composition. At the same growth conditions and the similar In-composition for two MQWs, PDMQWs present a longer emission wavelength with an extra emission peak from In-rich nanodot-like structures, compared with that of NDMQWs. Mg memory effect introduces high concentrations of Mg residual in PDMQWs accompanying with the incorporation of C, H, and O impurities, which impose negative influence on the optical properties of PDMQWs. The potentials and problems, as well as the possible problem-solving methods of p-side down light-emitting diodes (PDLEDs) in developing long wavelength emitter were also discussed, which may bring some new thinkings for the design of III-nitrides PDLEDs.

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1. Introduction

III-nitrides long-wavelength light-emitting diodes (LEDs), such as yellow, amber and red LEDs, are of importance in full color displays, monolithic white LEDs and solid state lighting [1–6]. However, the III-nitrides long-wavelength LEDs, especially in yellow emission range, still exhibit low internal quantum efficiencies (IQE) as compared to those of InAlGaP LEDs [1]. To date, though the physical origin of low efficiency in III-nitrides long-wavelength LEDs is still under debate, the properties of high In-composition InGaN in the multiple quantum wells (MQWs) is believed increasingly to be a key issue [1–4]. One primary point is In-rich InGaN quality degradation resulting from the low temperature growth process of InGaN quantum wells (QWs), large lattice mismatch between InGaN and GaN, and high temperature destruction during the epitaxial process after the growth of MQWs [1,2]. The other important point is the energy band bending and reduced overlap between electron and hole wave functions in MQWs due to the quantum confined Stark effect (QCSE), mainly caused by the piezoelectric polarization field [1–4]. These two points become even worse for the high In-composition and thick QWs, two necessities for the long-wavelength emission LEDs.

In order to weaken the QCSE and improve the efficiency of III-nitrides LEDs, various methods depended on the mechanism of regulating the polarization field in MQWs are applied into device design and material growth, including MQWs energy band engineering [1,2], quantum dots (QDs) [3], nano-structure [4], non-polar and semipolar substrates [5], and strain pre-relief layer [6]. Recently, based on reversing the direction of polarization field instead of regulating it, the concept of reversed polarization LEDs (RPLEDs) has been proposed, which indicates enhancing the electric field in the MQWs by applied forward bias or polarization fields [7–13]. Conventional LEDs are grown along the [0 0 0 1] orientation on top of the Ga-polar n-type underlying layer with p-type cladding layer grown on top of the MQWs, which are called normal polarization LEDs (NPLEDs) structures. In general, RPLEDs can be achieved using a p-side down structure (p-type cladding layer is grown before MQWs) with Ga-polar III-nitrides or n-side down structure (n-type cladding layer is grown before MQWs) with N-polar III-nitrides [7]. However, the growth of N-polar III-nitrides by metal–organic chemical vapor deposition (MOCVD) is a challenging task due to the formation of hexagonal hillocks and the incorporation of high concentrations of background impurities, which limit the development of RPLEDs using N-polar III-nitrides. Considering that the Ga-polar LEDs on sapphire substrates grown by MOCVD have been commercialized with smooth surface morphology and excellent electrical and optical properties, the growth of RPLEDs with p-side down structures (PDLEDs) using Ga-polar III-nitrides can be compatible with the currently large-scale and commercial LEDs techniques.

PDLEDs present several advantages for the development of long-wavelength emission emitters. For PDLEDs, the growth temperature of the p-GaN could be higher for the better electrical and crystalline quality without damaging the high In-composition MQWs, which may otherwise be subjected to the potentially damage by the high temperature required for the growth and annealing of Mg-doped AlGaN and GaN epilayers in conventional n-side down LED (NDLEDs). In addition, since it is much easier to grow n-type GaN with good crystalline quality and low sheet resistance even at much lower temperature, more In incorporation and better surface current spreading can be realized in PDLEDs, which are favorable for long-wavelength emission and electrode fabrication of LEDs. Moreover, PDLEDs allow a more stable emission wavelength with little blueshift even at the high current densities, enabling improved efficiency for long-wavelength devices [12,13]. Some numerical simulations and experimental results also demonstrate several merits of PDLEDs in decreasing electron overflow, improving hole injection efficiency and reducing turn on voltage [10–13]. Since the first report of PDLEDs more than a decade ago, many achievements have been realized to solve the electricity-related problems of PDLEDs varied in the growth of low resistance buried p-GaN, lateral current spreading of resistive buried p-GaN and activation of buried p-GaN [14–18]. However, the recent performance of PDLEDs presented by experimental results are still relatively low as compared with that of conventional NDLEDs, which are related to the few studies and poor understanding of MQWs properties in PDLEDs. Due to the reversed epitaxial sequence and device structure, the MQWs in PDLEDs present different properties as compared with that of MQWs in NDLEDs, which influence device performance greatly and deserve more investigation.

In this work, using Ga-polar III-nitrides oriented along the [0 0 0 1] direction, the normal polarization n-side down multiple quantum wells (NDMQWs) and reversed polarization p-side down multiple quantum wells (PDMQWs) structures with yellow emission were grown by MOCVD on sapphire substrates. The surface morphology, interface quality, optical properties, and impurities distribution of PDMQWs were investigated and compared with those of NDMQWs. The potentials and problems, as well as the possible problem-solving methods of PDLEDs in developing long-wavelength LEDs were also discussed.

2. Experiments

The NDMQWs and PDMQWs structures were grown by MOCVD in a 3 × 2 in. Aixtron close-coupled showerhead reactor on sapphire (0 0 0 1) substrates. The trimethylgallium (TMGa), trimethylindium (TMI), and ammonia (NH_3) were used as Ga, In and N sources, respectively. Biscyclopentadienyl magnesium (CP_2Mg) and silane (SiH_4) were used as p-type and n-type GaN dopants, respectively. Triethylgallium (TEGa) was used as the Ga source for the growth of the MQWs. For PDMQWs structure, a 2-μm-thick undoped GaN (u-GaN) was first grown at 1080 °C, following the deposition of a 1-μm-thick Mg-doped GaN (p-GaN) underlying layer at 990 °C with Mg doped concentration of $6 \times 10^{19}\ \mathrm{cm}^{-3}$. The Mg source was turned off after the growth of p-GaN for thermal annealing to activate the p-GaN at 750 °C. The MQW active layers consisted of five pairs of 4-nm-thick InGaN quantum wells (QWs) and 16-nm-thick u-GaN quantum barriers (QBs). The growth temperatures for QWs and QBs were 720 and 765 °C, respectively. For the NDMQWs structure, the growth conditions for the MQWs were the same to those of PDMQWs structure except that the NDMQWs structure was grown on the 1 μm-thick n-GaN underlying layer.

The surface morphologies of u-GaN, n-GaN and p-GaN underlying layers, and the two MQWs were viewed by atomic force microscope (AFM) with a tapping mode. Scanning electron microscopy (SEM) measurements were also performed to measure the surface morphologies of two MQWs. High-resolution X-ray diffraction (HRXRD) measurements were carried out at room temperature (RT) to determine crystalline quality of u-GaN, n-GaN and p-GaN underlying layers. The photoluminescence (PL) spectra of two MQWs were characterized by 405 nm laser at RT using an HR300 CCD spectrometer. A secondary ion mass spectroscopy (SIMS) was used to probe the concentrations of elements in the two samples.

3. Results and discussion

In the SEM diagram of NDMQWs in Fig. 1(a), trench-like characteristics can be clearly observed which mostly form close loop