Various misfit dislocations in green and yellow GaInN/GaN light emitting diodes

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We report the growth and structural characteristics of green and yellow (529–576 nm) GaInN/GaN light emitting diodes (LEDs) grown on two types of c-plane substrates – bulk GaN and sapphire. In this longer wavelength range, depending on the substrate, we find different strain relaxation mechanisms within the GaInN/GaN quantum well (QW) region. In optimized epitaxy, structures on sapphire that contain a low density of threading dislocations (TDs) within the n-GaN show virtually no generation of additional misfit dislocations (MDs) (<10⁸ cm⁻²) or V-defects within the QW region for emission wavelengths up to 571 nm. On bulk GaN substrate, however, where much fewer TDs reach the QWs, strain relaxation is observed by inclined dislocation pairs in green emitters and a high density of edge-type MDs in yellow emitters. The electroluminescence line width, as well as the efficiency droop, was found to increase with dislocation density in the QWs.

1 Introduction

Green and yellow GaInN/GaN light emitting diodes (LEDs) are essential components for energy-efficient RGB and RGBY solid-state white lighting with good color rendering and high customer satisfaction. Efficiency in that range, however, is still below that of GaInN-based blue and AlGaInP-based red emitters. The challenge in closing this “green gap” lies in the incorporation of sufficient InN into the GaInN quantum wells (QWs) of the active region without degrading the crystalline perfection and epitaxial homogeneity [1]. Here, yellow emitters pose an even higher challenge than the green ones. They require management of higher biaxial strain within this lattice mismatched system and its propensity for defect generation, such as misfit dislocations (MDs) [2] and V-defect [3] formation. For heteroepitaxy on sapphire, the active region will have to be grown on layers that already contain a high density network of threading dislocations (TDs) on the order 10⁸–10⁹ cm⁻². Our earlier work has shown that all such defects need to be avoided or reduced to boost LED efficiency, particularly in the longer wavelength regions of green [1], and likely also in the yellow. Bulk GaN substrates, obtained by hydride vapor phase epitaxy (HVPE) [4], prove a solution due to dislocation densities as low as 5 × 10⁶ cm⁻².

Here we compare LEDs grown on bulk GaN and sapphire substrates with emission wavelength from green to yellow (529–576 nm). We characterize the structural properties by means of cross-sectional transmission electron microscopy (TEM) and LED performance by electroluminescence (EL) spectroscopy.

2 Experimental

Two types of c-axis grown c-plane GaN templates were used in this study: bulk GaN and 5-μm-thick GaN on c-plane sapphire. The bulk GaN substrates of size 1 cm × 1 cm were obtained by HVPE and have a dislocation density as low as 5 × 10⁶ cm⁻². Both templates have a surface roughness of 0.1–0.2 nm (root mean square), as measured by atomic force microscopy. LED structures were grown on both templates by metalorganic vapor phase epitaxy. Growth conditions were adopted to suppress V-defect generation [5, 6]. Active regions consisting of 8 or 10 pairs of GaInN/GaN QWs were sandwiched between the 1-μm-thick overgrown n-GaN and 180-nm-thick p-GaN. The normal QW and barrier thicknesses are 3
and 20–25 nm, respectively. A 15-nm-thick $\text{Al}_{0.18}\text{Ga}_{0.82}\text{N}$ electron blocking layer was inserted between the last barrier and the $p$-GaN. EL of the full LED epi wafer was characterized using scratch diodes with 1 mm diameter indium contacts. LEDs with peak emission wavelengths from 529 nm (green) to 576 nm (yellow) at 20 mA (current density $2.5 \text{ A/cm}^2$) are included in this study. As determined by X-ray diffraction, the average InN fraction in the QW ranges from 8 to 12%, though we are aware that other groups quote higher numbers to reach these wavelength ranges [7]. Small sample portions were prepared for TEM analysis by standard mechanical polishing and low angle ion milling at 5 kV. Bright field and high-resolution TEM images were recorded on PHILIPS CM12 TEM (120 kV) and JEOL 2010 TEM (200 kV).

3 Results and discussion

We generally find that emission wavelength is shorter in LEDs on bulk GaN than on sapphire even when grown in the same run. At 529 nm on bulk, the difference is around 30 nm. The X-ray diffraction measurement shows a lower InN fraction. This may be caused by the higher thermal conductivity and lower wafer bowing in bulk GaN, resulting in a higher surface growth temperature. The TEM analysis also reveals substantially different dislocation networks in both structures at such long wavelengths.

TEM images of the LEDs on sapphire are shown in Fig. 1. Ten pairs of QWs can clearly be distinguished in the 529 nm (Fig. 1a) and 549 nm (Fig. 1b) LEDs. Within the microscope viewing range over 10 μm, no V-defects and only a few MDs ($<1 \times 10^9 \text{ cm}^{-2}$) were found to be generated in the QW region. QW and barrier thickness are found to be rather uniform all across the areas analyzed. The 571 nm yellow LED on sapphire (Fig. 1c), at low magnification to cover a stretch of 8 μm, shows no trace of MD initiated in the QWs. In a blown-up portion (Fig. 1d), we confirm the good crystalline quality of the active region. From these micrographs, the TD density in the QWs is determined to be $5 \times 10^8-2 \times 10^9 \text{ cm}^{-2}$ for these three samples. From X-ray reciprocal spacing mapping (RSM) in all those samples (data not shown here), we find the GaInN/GaN QWs are fully strained to the GaN templates underneath.

TEM micrographs of the LEDs on bulk GaN are shown in Fig. 2. We find no defect generation in the homo-epitaxy interface. Instead, defect initiation within the QWs is observed. For the 529 nm green LED on bulk GaN (Fig. 2a), we find that all dislocations are inclined from the growth direction and most of those come in pairs [8]. Two dislocations in one inclined dislocation pair (IDP) originate in the same QW and show a high geometric symmetry. They tilt to equivalent $\{11\overline{2}0\}$ directions by 18–23°. When viewed from the top, they form a 120 or 180° pattern. Their formation can be well explained by lattice relaxation through the removal of lattice points between the two dislocation cores [8]. The total dislocation density is $\sim6 \times 10^8 \text{ cm}^{-2}$. By X-ray RSM, partial relaxation of the averaged strain by some 5% was found for the MQW. We attribute this to the formation of IDPs.

For the 576 nm yellow LED on bulk GaN, we find a high density of MDs ($\sim2 \times 10^{10} \text{ cm}^{-2}$) generated inside the QWs. TDs initiated by those dislocations are not inclined, but propagate along the $c$-axis growth direction. Figure 2b and c are taken along different diffraction $g$ vectors. All dislocations come out of contrast when $g=\{0002\}$. Using the invisibility criterion, we determine that they are edge-type with Burgers vector $1/3[11\overline{2}0]$. Apparently, in the absence of TDs penetrating from the GaN, higher strain is accumulated in the QW resulting in the

![Figure 1](online color at: www.pss-a.com)

Bright field TEM images of LEDs on sapphire with different emission wavelength: (a) 529 nm, (b) 549 nm, and (c) 571 nm. (d) Blown-up portion of (c). Very few MDs were generated in the active region of these structures.
generation of new dislocations, in particular IDPs and MDs as observed here.

Light output power (LOP) was measured as collected from the backside of the wafers. Resulting partial external quantum efficiency (EQE) is shown in Fig. 3a. Maxima are reached at low current density (0.6–1 A/cm²), where green (529 nm) and yellow (576 nm) LEDs on bulk GaN show 9.9 and 2.6%, respectively. These values are 30 and 36% higher than the same wavelength LEDs on sapphire. This may be due to the lower detriment of the purely edge-type dislocations in IDPs in contrast to the mixed dislocations on sapphire. The efficiency of LEDs on bulk GaN, however, drops by 65% (green) and 79% (yellow) when current density increases from 1 to 25 A/cm². Over the same range, efficiency in LEDs on sapphire drops only 49% (green) and 36% (yellow). The higher efficiency droop of LEDs on bulk GaN is probably caused by the higher density of dislocations in their active region.

The inset of Fig. 3b shows the EL spectra of green and yellow LEDs on sapphire (black curve) and bulk GaN (red curve) substrates at 20 mA. We notice that EL peaks are broader for the LEDs on bulk GaN than on sapphire. The EL line width with the density of dislocations in the QWs (sum of TDs penetrating through QWs from the template and QW-generated MDs) is shown in Fig. 3b. The red squares represent LEDs on bulk GaN while the black triangles stand for LEDs on sapphire. As the density of dislocations rises from $5 \times 10^8$ to $2 \times 10^{10}$ cm⁻², the spectral line width increases from 180 to 240 meV. This is mostly the result of a secondary, shorter wavelength peak that emerges, but also contributed to by a longer wavelength tail. This secondary peak resembles the band-to-band transition seen in stimulated emission in other samples while the primary peak likely originates in polarization-induced excitonic recombination. It is likely that the different dislocation densities are responsible for these differences. It should be noted that
the formation of high densities of IDPs is not an inherent limitation of the bulk GaN substrate but rather reflects the higher challenge to avoid strain relaxation in the active region on such higher quality substrates.

4 Conclusion We studied the structural and optical properties of c-axis grown green and yellow LEDs, both, on c-plane sapphire and bulk GaN substrates. We demonstrate that LED epitaxy on sapphire can be performed in such a way, that the high density of TDs from n-GaN template does not lead to generation of MDs in the active region up to emission wavelengths as long as 571 nm. For LEDs on bulk GaN in the same wavelength range, the low defect density of the substrate can be repeated throughout the epitaxial n-GaN. In their QWs, however, generation of MDs and IDPs leading to strain relaxation was observed. We find that efficiency droop and line widths of EL spectra increase with dislocation density in the active region. We conclude that dislocation densities in the active region need to be reduced further to improve the performance of LEDs at high-current density.

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