Dislocation analysis in homoepitaxial GaInN/GaN light emitting diode growth

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Abstract

We demonstrate homoepitaxial growth of GaInN/GaN-based light emitting diodes (LED) on quasi-bulk GaN with an atomically flat polished surface. The threading dislocation densities of the epitaxial layers were 2–5 \times 10^{8} \text{ cm}^{-2} which was one order of magnitude less than those grown on c-plane sapphire substrate. The growth defects introduced during the epitaxial process were also one order of magnitude smaller than those grown on the sapphire substrate. The crystalline quality and the optical properties of the epitaxial layer and device performance were much improved. The optical output power of the light emitting diode increased by more than one order of magnitude compared to those on sapphire substrate.

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1. Introduction

Group III-nitride device development still suffers from mismatched heteroepitaxial growth. Mismatch in lattice constants and thermal expansion coefficients between substrate, mostly sapphire or SiC, and epitaxial layer inhibits perfect crystal formation, resulting in high densities of threading dislocations. In heteroepitaxial GaN, threading dislocations as high as 10^{9}–10^{11} \text{ cm}^{-2} are common place \cite{1} unless specialized multi-step re-growth methods are being applied \cite{2–4}. Low dislocation density bulk GaN has therefore long been sought for as the ideal substrate for homoepitaxial growth. The main challenges are: (1) to obtain epitaxial production worthy sized bulk crystals of such high qualities, and (2) to replicate the bulk performance in epitaxial overgrowth.

One very promising approach has been to grow thick layers of GaN in hydride vapor-phase epitaxy (HVPE) \cite{5}. In such material, threading dislocation densities, as judged by cathodoluminescence (CL) of the top surface \cite{6}, can routinely reach values as low 10^{6} \text{ cm}^{-2} and even 10^{5} \text{ cm}^{-2}. Wafers up to the dimensions of 2 inch are commercially available \cite{7,8}. The second challenge now calls for metal-organic vapor-phase epitaxy (MOVPE) to replicate the low dislocation density in homoepitaxial films on these substrates.

2. Experimental procedure

There were two types of GaN templates used in this work: (1) 300 \mu m thick free standing HVPE GaN; and (2) 2 \mu m thick MOVPE GaN on 330 \mu m thick c-plane sapphire. HVPE GaN and MOVPE GaN templates were n-type doped with Si donor concentrations of 1 \times 10^{18} and
respectively. CL was used to quantify dislocation densities on both types of samples. The acceleration voltage, probing current and objective aperture used in CL measurement were 10 kV, 600 pA and 50 μm, respectively. These CL probing conditions were confirmed not to introduce any degradation to the active regions of the samples.

3. Results and discussion

3.1. Comparison of device performance

(0 0 0 2) XRD curves confirmed the superlattice periods of 8.5 and 8.8 nm for GaInN/GaN active regions in LED on GaN and LED on sapphire as designed, respectively. A higher number of satellite peaks as well as one order of magnitude higher satellite peak intensities derived from the active region of the LED on GaN samples suggested superior crystalline quality and sharper interface of the GaInN quantum well (QW) and GaN barrier compared to those of the LED on sapphire samples. Fitting of the (0 0 2) XRD curves assuming that the GaInN QW layers were pseudomorphically grown on GaN, yielded indium contents of 13% and 9% for LED on GaN and sapphire, respectively. Though the difference in indium incorporation could be explained by compressive strain and/or template temperature, it will require further systematic study to clarify this discrepancy.

As shown in Fig. 1, PL peak wavelengths observed for as-grown LED on GaN and sapphire, were 440 and 420 nm, respectively. The PL results agrees with (0 0 2) XRD results and reconfirmed that indium incorporation was higher in GaInN QW layers in LED on GaN compared to that of the LED on sapphire. Moreover, the peak intensity of the LED on GaN was 20 times as strong as that of the LED on sapphire. This big difference

Table 1
RMS of the surface roughness of the LEDs on GaN and sapphire before and after the homoepitaxial growth

<table>
<thead>
<tr>
<th>Samples</th>
<th>Pre-homoepitaxial growth (nm)</th>
<th>Post-homoepitaxial growth (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LED on GaN</td>
<td>0.160</td>
<td>0.272</td>
</tr>
<tr>
<td>LED on sapphire</td>
<td>0.206</td>
<td>0.373</td>
</tr>
</tbody>
</table>

Fig. 1. Photoluminescence spectra of as-grown LED on GaN and LED on sapphire.
cannot be solely explained by the difference of the indium content.

The optical output power of fully fabricated LED dies was collected through the templates using a calibrated spectrometer system consisting of integration sphere, optical fiber and a charge coupled device (CCD). As depicted in Fig. 2, electroluminescence intensities of the LED on GaN were much stronger than those of the LED on sapphire when operating under the same driving current. At driving current of 0.5 A, the radiation power of the LED on GaN could reach 7 mW. Also, the LED on GaN’s driving current could achieve values as high as 600 mA, which is much higher than the LED on sapphire. The latter reached the voltage limit of 7 V in the testing system at the driving current of only 80 mA. This result suggests the suitability of bulk GaN as a homoepitaxial template for high optical output power LEDs and hence solid state lighting applications.

3.2. Evaluation of threading dislocation density

From an analysis by AFM (Fig. 3) we achieved threading dislocation densities in the heteroepitaxial GaN on c-plane sapphire as low as mid-10^6 cm^{-2} as exhibited in Table 2. The threading dislocation densities on HVPE GaN were found to be about mid-10^6 to lower than 10^6 cm^{-2}. After the homoepitaxial growth, threading dislocation densities in both samples increased to the lower than 10^8 and lower than 10^9 cm^{-2} for the LEDs on GaN and sapphire, respectively. Jasinski et al. [9] reported that the threading dislocations on MOVPE grown GaN and GaInN layers on quasi-bulk GaN templates were propagated directly from the template. The resulting threading dislocation densities of the homoepitaxial layers hence were of the same order of magnitude as those of the quasi-bulk GaN itself. The heavily doped Mg might initiate micro-structural defects in p-GaN and lead to formation of additional dislocations. However, the process of newly formed dislocations which increased the threading dislocation densities in both samples by one order of magnitude was unknown. Investigations by transmission electron microscopy will be required to further investigate the nature of dislocations formed in the homoepitaxial layers. Nevertheless, this result suggests that existing dislocations could play a major role in the expansion of dislocation densities in the homoepitaxial growth (Fig. 3).

Using scanning electron microscopy (SEM), the number of epitaxial defects, i.e., hexagonal pits, could be determined (Fig. 4). These defects appeared as dark spots in CL images taken at the peak wavelength of each sample. In the CL image of the LED on GaN there were bands of low intensity areas while there were high densities of low intensity spots scattered randomly over the mesa area. It was very difficult to identify dislocation related dark spots on either sample. The pit densities were 7 × 10^4–3.6 × 10^5 cm^{-2} for the LED on GaN which were almost one order of magnitude smaller than those found on the LED.
on sapphire where defect densities were approximately $1\text{–}2 \times 10^6 \text{cm}^{-2}$.

However, when observing the LED on GaN at lower temperatures, i.e., 77–150 K, we observed an additional number of dark spots besides those pits as shown in Fig. 5. These additional dark spots represented dislocations formed in the regrown epitaxial layers. The corresponding dislocation densities were found to be about $2 \times 10^6$ and $5 \times 10^6 \text{cm}^{-2}$ at 438 and 385 nm, respectively. At 385 nm, there was strong emission observed from pits. The emission at 385 nm was attributed to donor–acceptor pair recombination. On the other hand, it was difficult to estimate more accurate densities of the dark spots for the LED on sapphire due to its high dislocation density.

For comparison, the CL images at 367 nm were collected from an etched n-GaN area. For the LED on GaN sample, there were a number of dark spots that clearly related to threading dislocations. The density of those dark spots was $4.5 \times 10^6 \text{cm}^{-2}$. This number was similar to those found for the LED on GaN at low temperature. However, it was still not clear at which epitaxial step threading dislocations with high densities in the mid-$10^8 \text{cm}^{-2}$ as observed by AFM, were developed. There are still a number of control parameters such as template cleaning procedure and growth conditions to optimize in order to further reduce the dislocation density in the homoepitaxial layer on such quasi-bulk HVPE GaN templates.

4. Conclusion

By analyzing AFM results, the threading dislocation densities of homoepitaxial GaInN/GaN LEDs on quasi-bulk HVPE GaN is found to be one order of magnitude lower than that of LEDs on sapphire. Besides, the number of growth pits increases with increasing threading dislocation densities in the substrate. The number of such growth defects was found to be one order of magnitude lower in the case of the quasi-bulk templates. Therefore, the homoepitaxial growth of LEDs on a quasi-bulk HVPE GaN benefited in terms of a lower threading dislocation density as well as lower growth defect density.

Overall, the optical properties and device performance were greatly improved when quasi-bulk templates were utilized. The PL intensity of the LED on GaN is 20 times stronger than that of the LED on sapphire. The maximum light output power of the LED on GaN is more than one order of magnitude higher than that of the LED on sapphire. This advantage of homoepitaxial growth using the quasi-bulk GaN templates will also be of interest for a broad range of further device applications.

References