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Long Wavelength GaN Blue Laser (400-490nm) Development Final Report 2000 for LLNL Project

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Final Report 2000 Final Report for LLNL Project

Long Wavelength GaN Blue Laser (400-490nm) Development

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EXECUTIVE SUMMARY

Room temperature (RT) pulsed operation of **blue** nitride based multi-quantum well (MQW) laser diodes grown on c-plane sapphire substrates was achieved. Atmospheric pressure MOCVD was used to grow the active region of the device which consisted of a 10 pair $In_{0.21}Ga_{0.79}N$ (2.5nm)/$In_{0.07}Ga_{0.93}N$ (5nm) InGaN MQW. The threshold current density was reduced by a factor of 2 from 10 kA/cm^2 for laser diodes grown on sapphire substrates to 4.8 kA/cm^2 for laser diodes grown on lateral epitaxial overgrowth (LEO) GaN on sapphire. Lasing wavelengths as long as 425nm were obtained. LEDs with emission wavelengths as long as 500nm were obtained by increasing the Indium content. These results show that a reduction in nonradiative recombination from a reduced dislocation density leads to a higher internal quantum efficiency. Further research on GaN based laser diodes is needed to extend the wavelength to 490nm which is required for numerous bio-detection applications. The GaN blue lasers will be used to stimulate fluorescence in special dye molecules when the dyes are attached to specific molecules or microorganisms. Fluorescein is one commonly used dye molecule for chemical and biological warfare agent detection, and its optimal excitation wavelength is 490 nm. InGaN alloys can be used to reach this wavelength.

I. INTRODUCTION

The development of blue lasers offers great potential for high density information storage, medical devices, and full-color displays. Since the report of the first RT pulsed operation of nitride based laser diodes by researchers at Nichia Chemical Industries two years ago [1] a handful of research groups in Japan and the United States have reported blue laser operation. Despite the significant progress by Nichia and others, the actual lasing mechanism and its relationship to the structural and electrical properties of these materials is not well understood. In this study we report on the growth of InGaN MQW and the properties of laser diodes made with InGaN MQW active regions.

RESULTS

InGaN multiple-quantum-well (MQW) laser diodes were grown by MOCVD in a two-flow horizontal reactor at both atmospheric and low pressure. In preparation for patterning a subsequent regrowth, a 2 μm thick GaN seed layer was grown on a c-plane sapphire substrate. A 2000 Å SiO_2 mask was patterned into stripes, oriented in the $<1\bar{1}00>_{GaN}$ direction, defining a 5 μm mask opening with a periodicity of 20 μm. After ~ 6 μm of lateral epitaxial overgrowth (LEO) GaN growth on the SiO_2 mask, the GaN stripes grew laterally and coalesced, forming a flat surface. The conditions for growth and coalescence of the LEO GaN are described elsewhere.[20] Next, the InGaN MQW laser structure was grown on both LEO GaN and on 2 μm GaN on sapphire. The structure had an active region consisting of a 3 period $In_{0.13}Ga_{0.87}N$ (40 Å) /$In_{0.04}Ga_{0.96}N$:Si (85 Å) MQW followed by a 200 Å $Al_{0.2}Ga_{0.8}N$:Mg cap. The n and p-type cladding regions surrounding the active region consisted of 25 Å $Al_{0.2}Ga_{0.8}N$ / 25 Å GaN superlattices with a total thickness of 0.45 μm. The cladding regions were Si-doped for the n-cladding and Mg-doped for the p-cladding. A 0.1 μm GaN:Mg layer was used as a contact layer and a 0.1 μm $In_{0.05}Ga_{0.95}N$:Si layer was used beneath the lower n-type cladding as a compliance layer.

Laser diodes were fabricated above the SiO_2 mask in the nearly dislocation-free wing regions, as well as above the coalescence fronts of the LEO GaN stripes. The laser cavity was oriented parallel to the direction of the SiO_2 stripes. Laser facets were formed by Cl_2 reactive ion etching (RIE) of 45 μm wide mesas of various lengths ranging from 400 μm to 1600 μm and p-contact stripes were patterned on these mesas with widths ranging from 5 μm to 15 μm. The structure was etched around the p-contact stripe through the p-cladding for index guiding. The n and p-contacts were formed by electron beam evaporation of Ti/Al and Pd/Au, respectively.

Figure 1 shows the PL from various QW active regions. The longest emission wavelength obtained was 500nm. LEDs were also fabricated from these active regions. Lasing was only obtained for wavelenths shorter than 420nm. The cause of the high threshold currents is most likely due to the alloy segregation in the higher indium containing alloys.

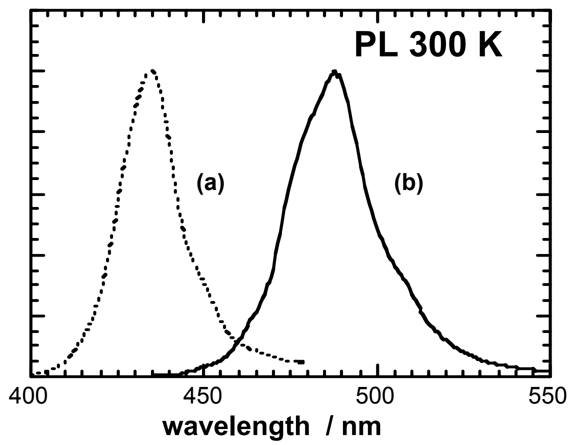

Figure 1 PL from InGaN quantum well active regions.

Lateral Epitaxial Overgrowth (LEO)

There are few or no threading dislocations generated at the coalescence fronts. Figure 2 shows cross-section TEM micrographs of the coalescence region. This high quality coalescence results from low wing tilts of the laterally growing stripes. The LEO wings have a tilt of 0.1^{o} relative to the underlying seed material, which was measured using x-ray diffraction as described earlier.[18]

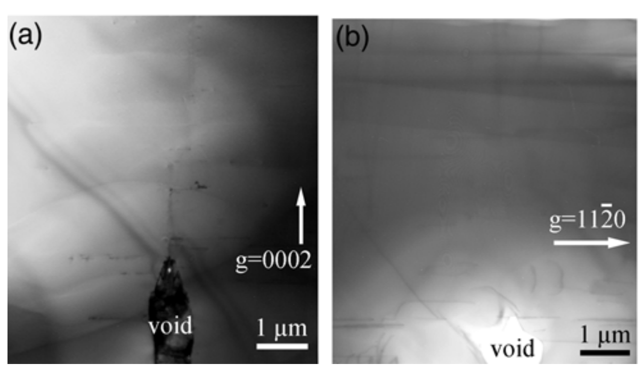

Figure 2: Bright-field cross-section TEM micrographs of a coalescence front viewed with (a) g = 0002 and (b) g = $11\bar{2}0$ two-beam conditions.

The threading dislocations in LEO GaN on sapphire are predominantly located in 'window' stripes every 15 μm, whereas structures on sapphire substrates have a more uniform dislocation distribution over the wafer. The dislocation distribution dominates the size of features in the surface morphology. Atomic force microscopy (AFM) was used to investigate the surface morphology for lasers grown on LEO GaN and laser grown on sapphire as seen in Figure 3. The surface morphology is drastically different for the two structures. The lasers on sapphire show small spirals uniformly distributed whereas on the LEO GaN the laser structure exhibits large spirals. These spirals grow in size until they meet another spiral. Each of these spirals is formed around a threading dislocation with a screw component. In the case of the LEO GaN, the threading dislocations are contained in the window region and are absent in the wing region. This is why all the spirals in the LEO case initiate in the narrow window regions and can grow quite large over the wing until it meets another spiral associated with a screw component threading dislocation from an adjacent window region forming a flat "trench-like" feature. In the case of the laser on sapphire, the spiral remain small because they meet neighboring spirals much more quickly due to the higher and more uniform dislocation distribution.

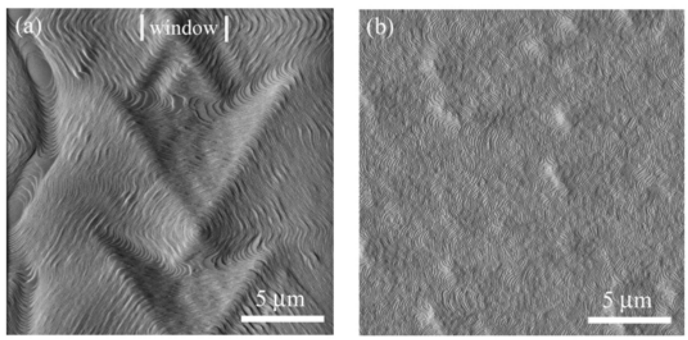

Figure 3: 20x20 μm2 amplitude AFM images of (a) a laser structure on LEO (b) a laser structure on sapphire. Note: The LEO stripes are running vertically.

Figure 4 shows the typical light output per uncoated facet of a laser diode grown on LEO GaN and a laser diode grown on GaN/sapphire as a function of forward current under pulsed operation. The minimum threshold current density was reduced by a factor of 2 from 10 kA/cm^2 for laser diodes grown on sapphire to 4.8 kA/cm^2 for laser diodes grown on LEO GaN on sapphire. The laser diodes on the LEO GaN showed this low threshold current density of 4.8 kA/cm^2 both above the SiO_2 mask regions and above the coalescence fronts of the LEO GaN. This reduction in threshold current density is attributed to a reduction in nonradiative recombination due to the lower dislocation density in the LEO GaN.

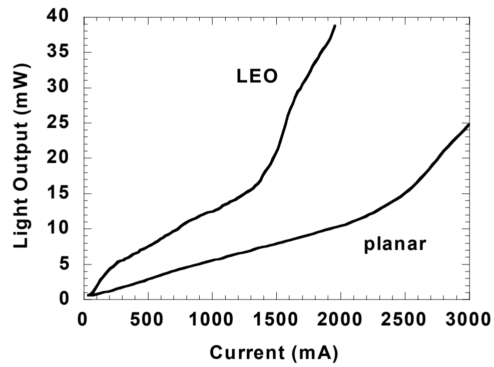

Figure 4: Typical light output per uncoated facet as a function of current for a laser diode grown on LEO GaN and a laser diode grown on sapphire.

Figure 5 shows the reciprocal of external differential quantum efficiency as a function of length for laser diodes grown on sapphire and LEO GaN. The external differential quantum efficiency of the laser diode increases with increasing internal quantum efficiency or decreasing internal optical loss as seen in the following relationship[21],

$$\eta_d = \eta_i \frac{\alpha_m}{\langle \alpha_i \rangle + \alpha_m} \tag{1}$$

where η_d is the external differential quantum efficiency, η_i is the internal quantum efficiency, α_m is the mirror loss and α_i is the internal optical loss of the laser. The mirror loss can be defined as

$$\alpha_m = \frac{1}{L} \ln\left(\frac{1}{R}\right) \tag{2}$$

where L is the length and R is the facet reflectivity. R is estimated to be approximately 0.053 for RIE etched facets.[22] Substituting Eqn. (2) into (1) and rearranging gives

$$\frac{1}{\eta_d} = \frac{1}{\eta_i} + \frac{\langle \alpha_i \rangle}{\eta_i \ln\left(\frac{1}{R}\right)} L \tag{3}$$

The internal quantum efficiency can be extracted from the y-intercept of Fig. 5 using Eqn. (3). The increase in external differential quantum efficiency seen in the lasers on LEO GaN compared to those on sapphire is due to an increase in the internal quantum efficiency from 3% to 22%. As mentioned, the reduced reverse bias leakage current in p-n junction diodes suggests the presence of mid-gap states due to threading dislocations.[23] These mid-gap states provide nonradiative recombination centers thereby decreasing the internal quantum efficiency. Reducing the dislocation density, and hence the mid-gap states, will result in an increased internal quantum efficiency. The same effect is also seen in the spontaneous emission portion of L-I curve below threshold in Fig. 2 as well as in LEDs fabricated on LEO GaN,[11,24] where the radiative efficiency increases with decreasing dislocation density.

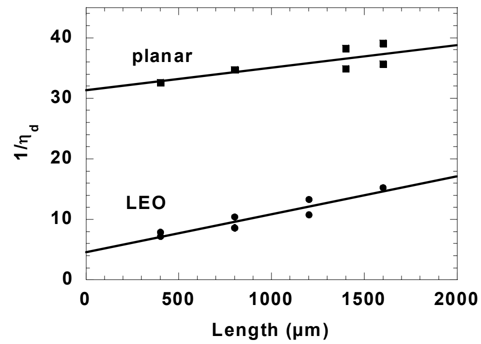

Figure 5: Inverse external differential quantum efficiency as a function of device length.

SUMMARY AND ACKNOWLEDGEMENTS

In summary, InGaN multi-quantum well laser diodes have been fabricated on fully coalesced laterally overgrown GaN on sapphire. The wing regions as well as the coalescence regions of the LEO GaN contain few or no threading dislocations. The threshold current density was reduced by a factor of 2 from 10 kA/cm^2 for laser diodes grown on sapphire substrates to 4.8 kA/cm^2 for laser diodes grown on LEO GaN on sapphire. These results show that a reduction in nonradiative recombination from a reduced dislocation density leads to a higher internal quantum efficiency. Lasing wavelengths as long as 425nm were obtained. LEDs with emission wavelengths as long as 500nm were obtained by increasing the Indium content. Further research on laser diodes is needed to extend the wavelength to 490nm which is required for numerous GaN based bio-chemical sensing applications. This work was performed under the auspices of the U.S. Department of Energy by the University of California Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

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