3D GaInN/GaN-based Green Light Emitters

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The GaInN/GaN-based quantum wells (QWs) on one of the naturally stable semipolar facets (the $\{11\bar{2}2\}$ *facet) have inferior properties than those on the other (the* $\{10\bar{1}1\}$ *facet). By optimizing the epitaxial growth conditions, the evolution of the* $\{11\bar{2}2\}$ *facets of GaN inverse pyramids were successfully suppressed achieving a 50 % higher photoluminescence (PL) intensity with even about 10 nm longer emission wavelength. The formation of structures with pure* $\{10\bar{1}1\}$ *facets could be enhanced by lower temperature, higher V/III ratio and lower filling factor of the* SiO_2 *selective growth mask. Complete light emitting diode (LED) structures were fabricated by using 3D GaN templates with GaInN/GaN-based QWs on the semipolar facets. A large leakage current occurring at the apex of the 3D structure was overcome by increasing the p-GaN growth time with 'pulse doping' which pushes the growth more vertically. The respective I-V curves show typical diode behavior.*

1. Introduction

Selective area growth (SAG) of group III nitrides allows the epitaxy of 3D GaN structures of high crystal quality with semipolar facets based on 2-inch sapphire substrates. The heavily reduced piezoelectric field on those semipolar facets compared to that on the c-plane promises a better device performance. A detailed description of the formation of the 3D structures can be found elsewhere [1].

The GaInN/GaN-based QW is a promising candidate for green light emitters which can be achieved as either an optically-pumped light converter [2] or an electrically-pumped conventional LED. The former has the great advantages of a better QW excitation homogeneity and a simpler structure without any doping or the AlGaN electron blocking layer (EBL). However, it requires a more complicated processing produre to integrate the conversion structures with excitation UV/blue LEDs compared to the conventional LEDs. In order to realize highly efficient green light emitting structures with both approaches mentioned above, we have investigated the epitaxial growth of inverse pyramid structures containing semipolar GaInN quantum wells on their side facets. Moreover, complete LED structures were fabricated by using 3D GaN templates with GaInN/GaN-based QWs on semipolar facets. During the overgrowth of p-(Al)GaN layers on the semipolar QWs, Mg-doping induces lateral growth. This results in a thin p-(Al)GaN layer on the apex of the n-GaN template causing a large leakage current. In order to overcome this problem, we increased the growth time when the vertical p-GaN growth is enhanced.

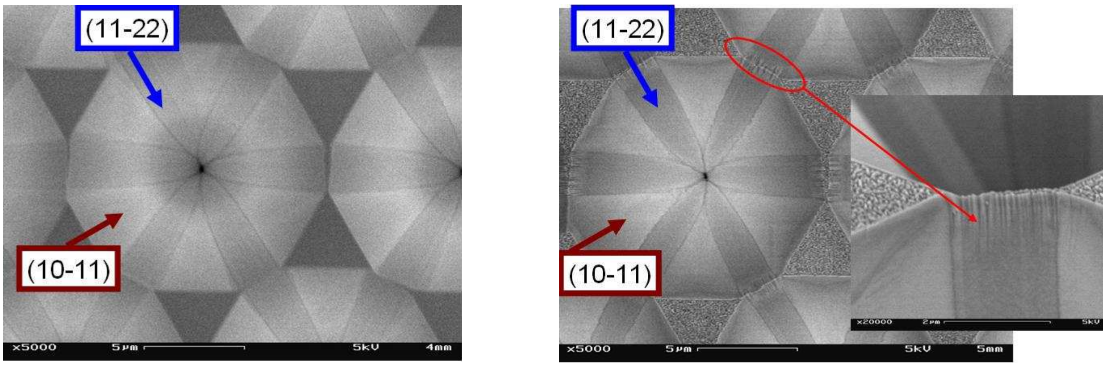

Fig. 1: Top view of the structure with both types of facets $\{10\bar{1}1\}$ and $\{11\bar{2}2\}$ before (left) and after (right) the growth of 5 GaInN/GaN QWs. The area close to the apex on the $\{11\bar{2}2\}$ facet is enlarged in the insert in the right-hand figure.

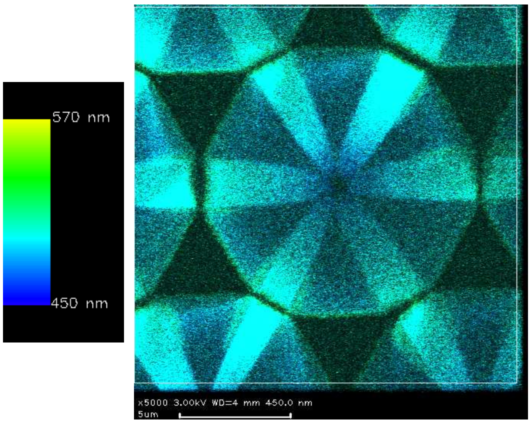

Fig. 2: Overlay of several CL mappings of the structure with both types of facets $\{10\bar{1}1\}$ and $\{11\bar{2}2\}$ after the GaInN/GaN QWs growth. The colors refer to the respective dominant wavelength.

2. Facet Control of GaN Inverse Pyramids

The crystal planes $\{10\bar{1}1\}$ and $\{11\bar{2}2\}$ are naturally stable semipolar facets for GaN inverse pyramids. When both types of crystal planes coexist, there are 12 facets on the surface. Such structures develop when reasonable growth conditions are applied (Fig. 1). According to the cathodoluminescence (CL) mapping for the structure with 5 GaInN/GaN QWs (Fig. 2), the emission wavelength is longer from the QWs on the $\{11\bar{2}2\}$ facet than from those on the other facet, different from our earlier studies [3]. This opposite behaviour may depend on different growth conditions. For such long wavelength quantum wells, we typically observe the formation of some mini-stripes near the apex of the $\{11\bar{2}2\}$ facets (see insert in Fig. 1, right). We measured locally resolved spectra on such a $\{11\bar{2}2\}$ facet within 8 excitation windows from top to bottom by CL (Fig. 3). The emission from the topmost excitation window – where we observe the mini-stripes – is relatively week and broad. From the second to the lowest excitation window, the emission is fairly strong and narrow with slightly decreasing intensity and a blue-shifting wavelength from top to bottom. Obviously, the mini-stripes developing during the GaInN/GaN MQW growth

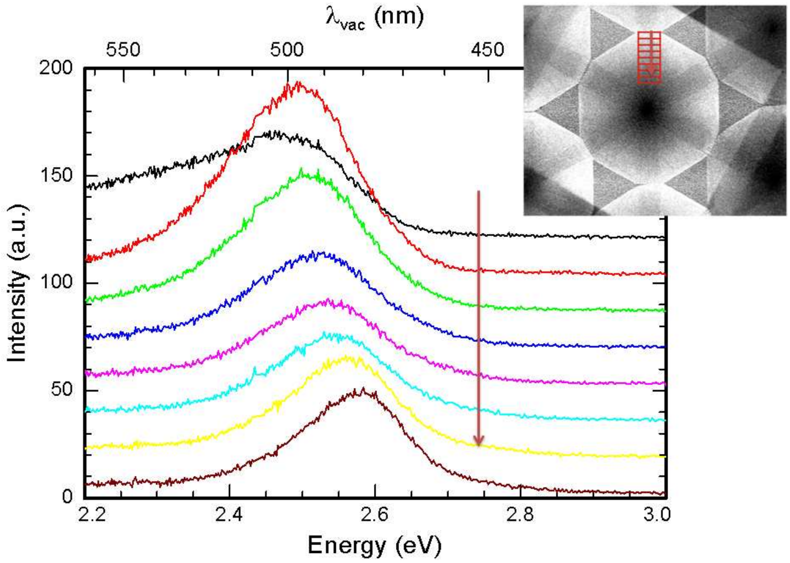

Fig. 3: CL linescan on the $\{11\bar{2}2\}$ facet from top to bottom. The insert shows a SEM top view on the investigated facets with the respective fields marked, in which the spectra have been measured.

degraded the QW quality causing a weak and broad emission. Therefore, our goal is to suppress the $\{11\bar{2}2\}$ facet on the GaN inverse pyramids due to the inferior properties of the mini-stripes.

Three parameters were varied during the growth of the GaN inverse pyramids to check their influence on the $\{11\bar{2}2\}$ facet suppression: The temperature, the V/III ratio, and the mask filling factor (the area ratio of the mask over the total surface) for the SiO_2 growth mask.

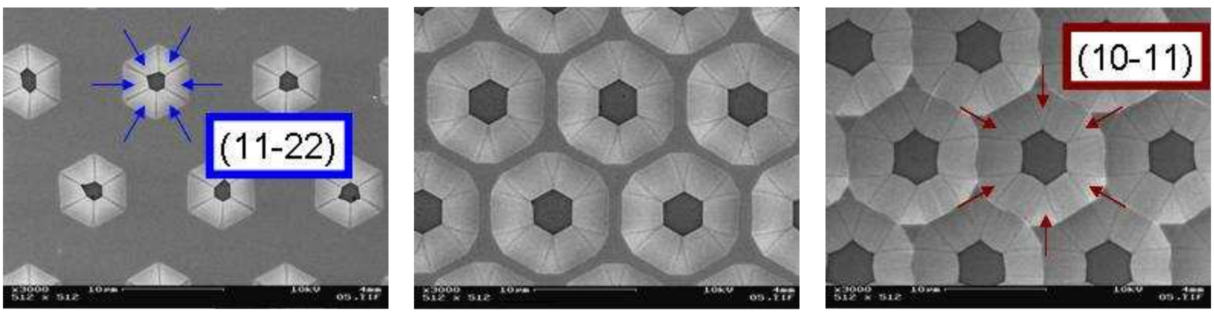

Fig. 4: Top view of GaN inverse pyramids grown at a temperature of 1120 °C (left), 1060 °C (middle) and 950 °C (right).

When decreasing the growth temperature from 1120 °C to 950 °C, we observed a steady transition from pure $\{11\bar{2}2\}$ facets to the increased appearance of $\{10\bar{1}1\}$ facets (Fig. 4). Similarly, the GaN inverse pyramidal surface is dominated by the $\{11\bar{2}2\}$ facet for a small V/III ratio of 200, getting gradually suppressed with increasing V/III ratio (Fig. 5). Finally, the $\{11\bar{2}2\}$ facet disappeared when the mask filling factor was reduced from 59 % to 25 % (Fig. 6).

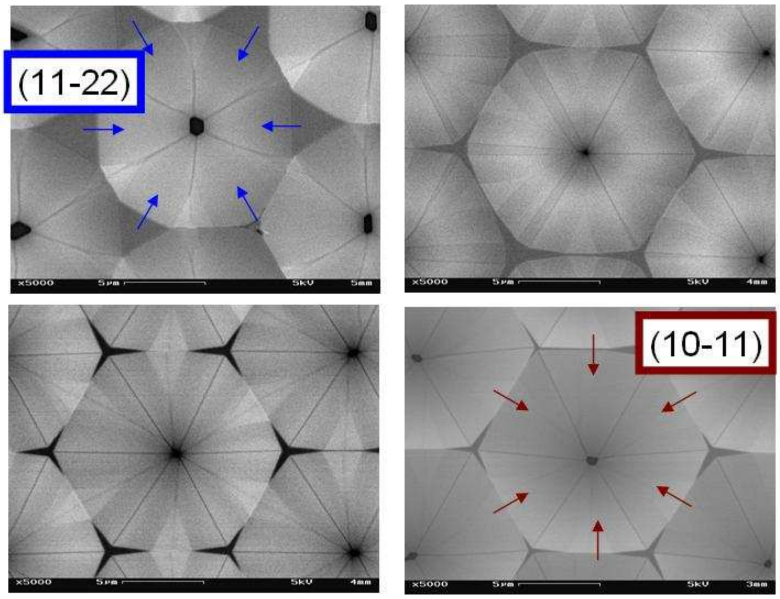

Fig. 5: Top view of GaN inverse pyramids grown with a V/III ratio of 200, 400, 500 and 700.

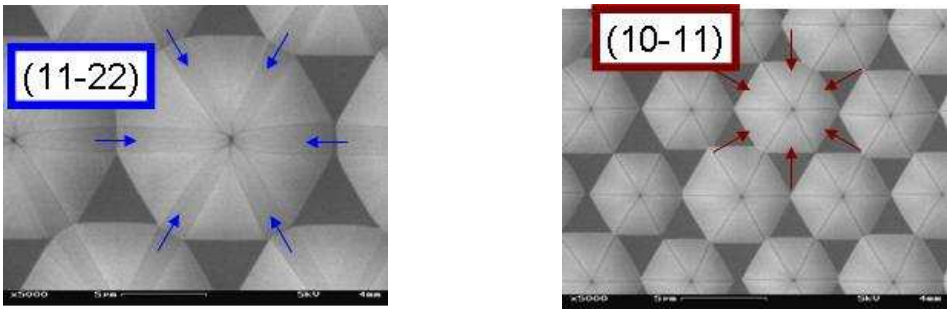

Fig. 6: Top view of GaN inverse pyramids with a mask filling factor of 59 % (left) and 25 % (right).

By applying the optimal values of the 3 parameters discussed above, the $\{11\bar{2}2\}$ facet was totally suppressed for a pure GaN structure without QWs (Fig. 7 (left)). Again, spectra were obtained from 8 excitation windows from top to bottom in CL (Fig. 8) for this optimized structure with 5 GaInN/GaN QWs (Fig. 7 (right)). The emission shows the trend of continuously decreasing intensity and blue-shifted wavelength from top to bottom without exceptions. The area within the first excitation window contributes to the strongest emission without suffering from the mini-stripes. The integrated photoluminescence of these structures peaking at 505 nm is about 50 % more intense as compared to the structure with the mini-stripes peaking at 494 nm.

In the top view of a structure without the $\{11\bar{2}2\}$ facet, but still grown with fairly low V/III ratio, three parts (one triangle and two symmetric neighboring parts as marked in Fig. 7) are observed within any of the 6 equivalent surface areas after the growth of the GaN layer below the quantum wells. The central triangle part is attributed to the facet $\{10\bar{1}1\}$ since its upper edge is parallel to the crystal direction $\langle 11\bar{2}0\rangle$ indicated by the growth mask alignment. The neighboring part could be either one single facet

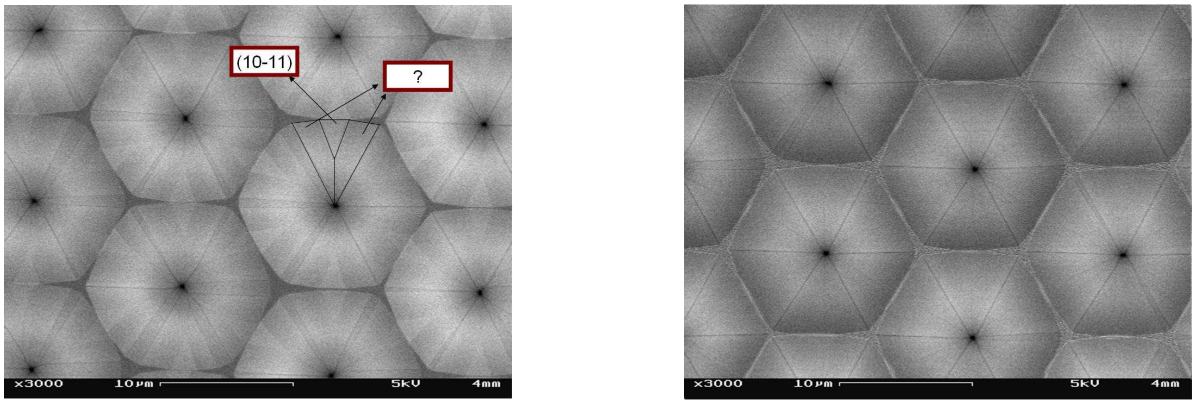

Fig. 7: Top view of the structure without the {11$\bar{2}$2} facets before (left) and after (right) the GaInN/GaN QWs growth. The three parts in any of the 6 equivalent surface areas are marked. The central triangular part is attributed to the {10$\bar{1}$1} facet. The other parts are attributed to unknown high-index facets very close to {10$\bar{1}$1}.

rotated by a slight angle with respect to the {10$\bar{1}$1} facet or several small facets with tiny misorientations among them. However, seemingly only one pure {10$\bar{1}$1} facet remains after the deposition of the 5 GaInN/GaN QWs. In spatially resolved CL mapping (Fig. 9) of the same structure with the 5 GaInN/GaN QWs, the 3 sub-facets are clearly resolved with longer emission wavelength from the two sub-facets as compared to the central triangle part. This may be explained by different In incorporation as a result of different surface orientations [4] needing more detailed studies. By increasing the V/III ratio to 700, the two neighboring parts are suppressed and GaN inverse pyramids with exclusively {10$\bar{1}$1} facets have been achieved (Fig. 10).

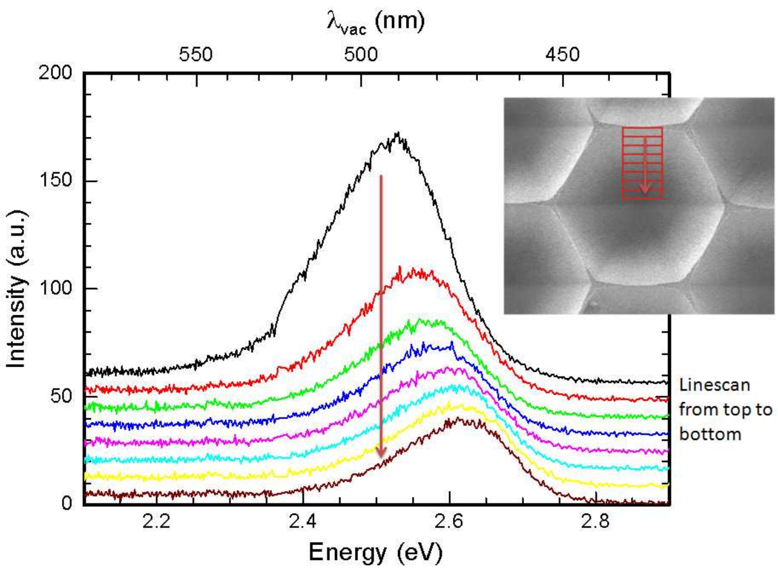

Fig. 8: CL linescan on the {10$\bar{1}$1} facet from top to bottom. Insert shows again the areas in which the spectra have been acquired.

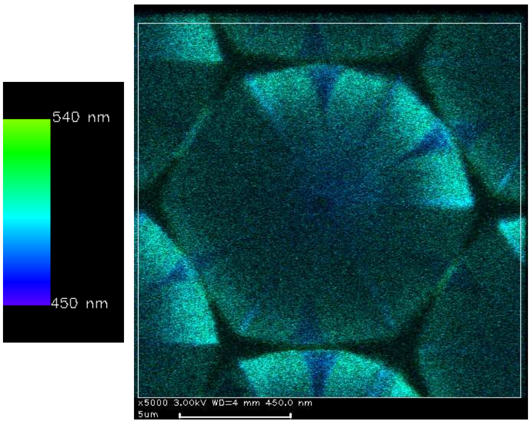

Fig. 9: CL mapping of the structure without the $\{11\bar{2}2\}$ facet after the GaInN/GaN QWs growth.

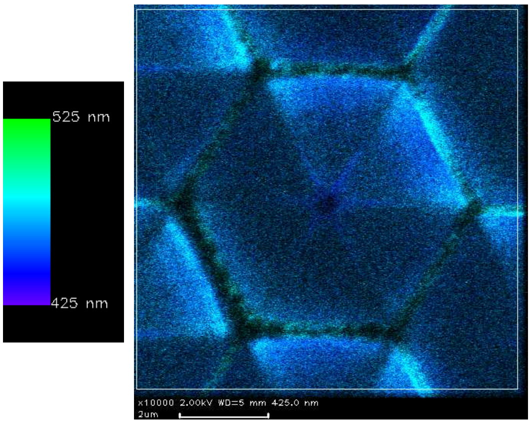

Fig. 10: CL mapping of the structure with exclusively $\{10\bar{1}1\}$ facets after the GaInN/GaN QW growth.

3. 3D µm-sized Light Emitting Diodes

For the fabrication of 3D-LEDs with semipolar quantum wells, the above-mentioned structures need to be overgrown by a p-doped GaN cap layer. The bottom part is now made of Si-doped GaN which normally forms a sharp apex. Mg doping induces lateral growth resulting in a plateau on the p-GaN surface with the sharp n-GaN apex underneath (Fig. 11 (left)). Therefore, the n-GaN apex might be either not covered by p-GaN at all or just overgrown by a very thin p-GaN layer. Hence, a too thin p-GaN layer causes large leakage currents in a LED device. A 'pulse doping' technique (the metalorganics and NH_3 are supplied alternatively in loops [5].) is helpful to push the p-GaN growth vertically. The total p-GaN layer was grown partly by normal epitaxy and partly by using the 'pulse doping'. This procedure was further optimized on striped LEDs since it is easier to check the p-GaN layer thickness by scanning electron microscopy than that of inverse pyramid LEDs. Indeed, the first stripe LED whose p-GaN was grown with the same parameters as the inverse pyramid LED suffered from such short-circuits in EL. The p-GaN on the n-GaN tip is only 57 nm thick. Therefore, we have doubled and tripled the growth time of

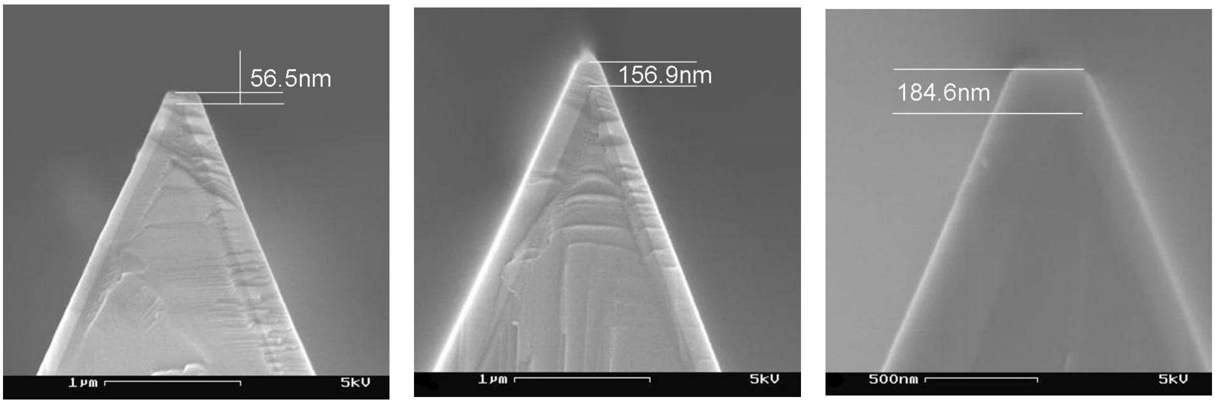

Fig. 11: Cross section view for the stripe LEDs with single, doubled and tripled pulse-doping p-GaN growth time, respectively (from left to right).

the pulse doped p-GaN. Now, the n-GaN tip is well isolated with at least 157 nm p-GaN on top (Fig. 11 (middle)). The current-voltage curves of the two latter structures show typical diode behavior (Fig. 12), although the light emission is still comparably weak requiring more optimization.

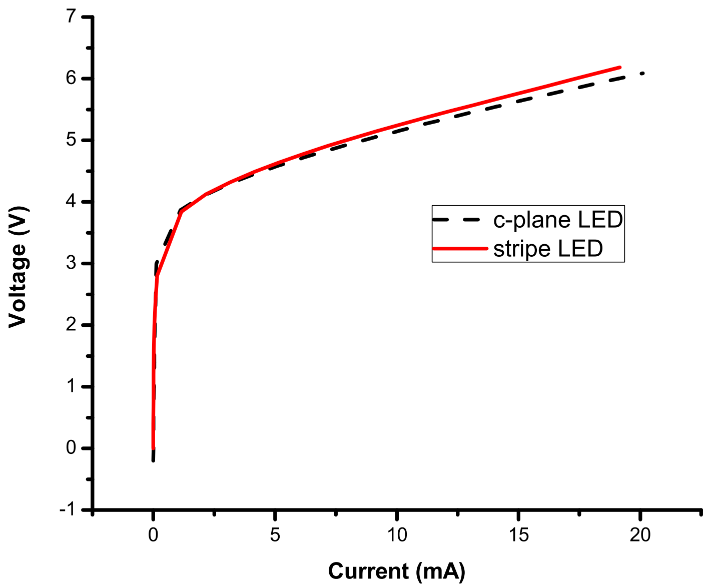

Fig. 12: I-V curve for the stripe LED with doubled pulse-doping p-GaN growth time.

4. Conclusion and Outlook

Luminescence conversion structures containing semipolar GaInN quantum wells are investigated on the basis of inverted pyramidal structures grown by selective area MOVPE. The formation of structures with pure $\{10\bar{1}1\}$ facets could be enforced by lower temperature, higher V/III ratio and lower mask filling factor. The formation of higher index facets close to $\{10\bar{1}1\}$ showing a better In incorporation needs more detailed studies. In order to optimize in particular the electrical characteristics of stripe LEDs, we have varied the thickness of the top p-layer which helped to suppress otherwise observed leakage currents. More optimization is necessary to enhance the output power of the stripe LEDs in EL, for example the GaN spacer thickness between the QWs and the p-AlGaN EBL, the Mg-doping profile and so on. We need to transfer the knowledge from stripe LED optimization to the inverse pyramidal structure as well.

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