Optimization of Semipolar GaInN/GaN Blue/Green Light Emitting Diodes on $\{1\bar{1}01\}$ GaN Side Facets

Thomas Wunderer

Bluish-green semipolar GaInN/GaN light emitting diodes (LEDs) were investigated as possible candidates for high-brightness devices even in the long wavelength visible regime. To combine the high material quality known from c-GaN and the advantages of a reduced piezoelectric field, the LED structures were realized on the $\{1\bar{1}01\}$ *side facets of selectively grown GaN stripes with triangular cross section. Structural investigations using transmission electron microscopy, scanning electron microscopy, high resolution x-ray diffraction, and atomic force microscopy have been performed and could be related to the luminescence properties in photoluminescence and cathodoluminescence. The defect-related luminescence peaks at 3.3 eV and 3.42 eV typically observed in planar non- and semipolar GaN structures as fingerprints of prismatic and basal plane stacking faults, respectively, could be eliminated in our facet LED structures by optimized growth conditions.*

Furthermore, indium incorporation efficiency for these $\{1\bar{1}01\}$ *facets is found to be about 50% higher as compared to c-plane growth, what helps significantly to achieve longer wavelength emission in spite of the reduced quantum confined Stark effect in such non- and semipolar materials.*

Combining these findings, we could realize a bluish-green semipolar light emitting diode on the side facets of our GaN stripes. Continuous wave on-wafer optical output powers as high as 240 µW @ 20 mA could be achieved for about 500 nm emission wavelength in electroluminescence measurements.

1. Introduction

The optical efficiency of current commercially available (Al,Ga,In)N light emitting diodes (LEDs) is found to decrease with increasing operation wavelength [1]. This is in large part caused by the local separation of electrons and holes in the quantum wells (QWs) as a consequence of strong internal piezoelectric fields in the biaxially compressively strained GaInN QWs. Besides the reduced recombination probability and the increased recombination time, this phenomenon, also known as the Quantum Confined Stark Effect (QCSE), leads to a red-shift of the effective emission wavelength.

To circumvent the negative effects of the high piezoelectric fields on the luminescence efficiency, it is highly desirable to grow GaInN/GaN heterostructures with reduced or vanishing internal piezoelectric fields. This can be achieved by rearranging the biaxial strain to planes other than the commonly used (0001) crystal plane [2]. Several groups are currently dealing with this subject by using the r-plane of sapphire, for instance, on which *a*-plane GaN can be grown [3, 4]. Other approaches make use of more exotic substrates like $LiAlO_2$ [5], on which pure *m*-plane GaN growth has been achieved. However, up to now the crystal quality of layers grown on such substrates cannot compete with that obtained on the more commonly used *c*-plane sapphire or SiC wafers, which still limits the optical performance of LEDs by using those substrates [6].

More recent investigations showed that also high brightness LEDs can be obtained on non- or semipolar GaN wafers [7–9]. But those results are based on only small GaN pieces in the size of 3 x (15-25) mm^2 which were sliced from high quality *c*-plane GaN grown by HVPE [8]. Those substrates provide a very low threading dislocation and stacking fault density [9], but their costs are forbiddingly high for any commercial application [10].

With the possibility for large-scale production, these problems may be overcome by starting the epitaxial growth in the conventionally used *c*-direction, and then forming GaN stripes with less polar side facets by selective epitaxy. QWs and even complete LED structures can then be grown on these facets [11–14]. Depending on the stripe orientation and growth conditions, different crystal facets can be achieved with reduced or even vanishing polarization fields. This could be verified in different studies [12, 14–16].

In this manuscript, we report on the optimization of the GaN stripe material quality with semipolar side facets. Structural properties using high resolution x-ray diffraction (HRXRD), atomic force microscopy (AFM) and transmission electron microscopy (TEM) can be correlated to characteristics in photo- and cathodoluminescence (PL,CL). The defect-related luminescence peaks at 3.3 eV and 3.42 eV observed in those studies could be eliminated by optimized growth conditions. Furthermore, the optimization of the QW emission in the green spectral range grown by selective epitaxy is another focus. Based on these studies, complete LED structures on the side facets are presented and the results of electroluminescence (EL) measurements are described for a device emitting in the bluish-green spectral range.

2. Experimental

The samples, undoped GaN stripes and complete LED structures, were grown by low pressure metalorganic vapor phase epitaxy (MOVPE). First, about 2 µm thick high quality GaN templates were grown on *c*-plane sapphire substrates including an in-situ SiN interlayer for efficient defect reduction [17]. After the deposition of 200 nm SiO_2 mask material via plasma enhanced chemical vapor deposition (PECVD) a stripe pattern is formed using photolithography and a dry etching step with reactive ion etching (RIE). The stripes are oriented along the $\langle 11\bar{2}0 \rangle$ GaN crystal direction. The parameters of the second epitaxial step have been tailored to grow triangularly shaped GaN stripes in the several µm wide mask openings which have $\{1\bar{1}01\}$ side facets as the most stable surface. Thereafter, for the LED sample, three GaInN quantum wells were grown covered by an AlGaN electron barrier and a GaN:Mg top layer. The nominal thickness of the GaInN QWs and the GaN barriers was determined to be about 4 nm and 8 nm, respectively. Further information on the growth and processing can be found elsewhere [14].

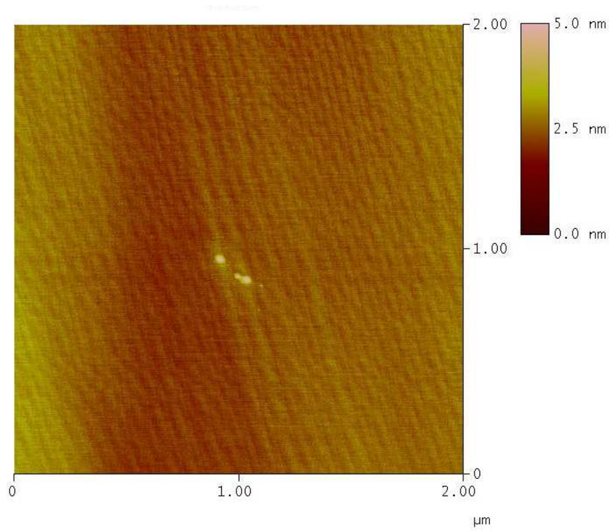

Fig. 1: 2 µm x 2 µm AFM scan of the semipolar $\{1\bar{1}01\}$ side facet of a LED structure using a special sample holder. A rms value as low as 0.25 nm was determined.

For the investigation of the structural properties, different measurement methods like HRXRD, AFM and TEM have been performed. The results could be correlated to luminescence characteristics using PL and CL. Besides, EL measurements were carried out for the LED samples emitting in the bluish-green spectral range.

3. Optimization of GaN Stripe Properties

3.1 HRXRD

First, HRXRD investigations have been performed to determine the crystal material quality of the GaN stripes. A broad beam spot of several mm^2 was used as an excitation source. Thus, the detected signal resulted from an integration over several stripes. However, the rocking curve of the $(1\bar{1}.1)$ reflection showed a relatively narrow full width at half maximum (FWHM) of 185 arcsec, whereby the stripes were oriented parallel to the plane of incidence of the x-ray beam.

3.2 AFM

Furthermore, the good material quality is comfirmed by AFM measurements. Fig. 1 shows an AFM scan of the $\{1\bar{1}01\}$ surface of a representative LED sample. For this purpose, a special holder with an inclined plane of 62° was used to orient the semipolar facet horizontally, exposing the facet to the top. The 2 µm x 2 µm scan shows a smooth surface with a rms value as low as 0.25 nm. Compared to other non- and semipolar GaN growth experiments [18–20] where only relatively rough surfaces could be achieved, this result confirms the advantage of the naturally stable surface and is one reason why the $\{1\bar{1}01\}$ plane is believed to be one of the favorable semipolar GaN planes.

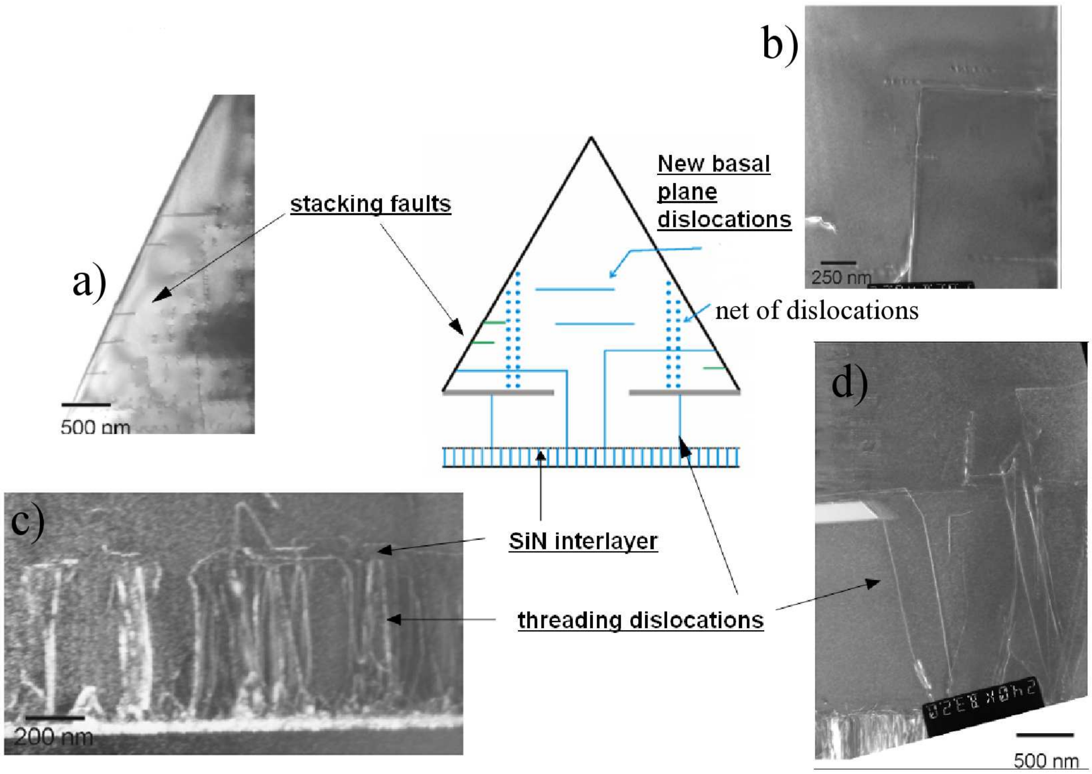

Fig. 2: TEM images from different regions of an undoped GaN stripe grown under not-optimized growth conditions. The dislocation density in the template is about $2 \times 10^8\,\mathrm{cm}^{-2}$.

3.3 TEM

Planar semi- and nonpolar GaN grown on different foreign substrates such as r-plane sapphire, a- and m-plane SiC, $LiAlO_2$ or $MgAl_2O_4$, etc. typically exhibit a high threading dislocation and stacking fault density [19–22]. The negative influence of these imperfections superposes the advantages of the reduction of the piezoelectric field in semi- and nonpolar materials and dominates the optical properties. That is why it is essential for high performance devices to provide good material quality with only few defects besides the reduced fields.

With respect to the defect situation in our samples, TEM investigations have been carried out for samples grown under different growth conditions. In Fig. 2 TEM images from different regions of an undoped sample are depicted. We want to point out that the GaN stripe in this specific sample was grown under unfavorable growth conditions. In Fig. 2 c) and d) one can see clearly how the threading dislocations start at the nucleation layer, propagate in growth direction and are stopped effectively through an in-situ deposited SiN interlayer. With the usage of an oxygen doped AlN nucleation layer most of the threading dislocations are edge type dislocations, whereas screw type dislocations are mostly avoided. As SiN can stop edge type dislocations effectively [23], our templates end up with a low dislocation density (all types) in the order of $2 \times 10^{8}\,\mathrm{cm}^{-2}$ for a $3\,\mu\mathrm{m}$ thick GaN template [17]. The few remaining dislocations which could penetrate the SiN interlayer are either stopped again by the mask material on top of the template or can proceed into the GaN stripe. It seems that not all dislocations from the template propagate into the GaN stripe, but some defects are annealed via the 2-step growth process. The remaining dislocations in the stripe running first in c-direction are then bent and continue their way in m-direction up to the semipolar surface of the facet (Fig. 2 b)).

Besides the threading dislocations originating from the template an ordered net of dislocations in the overgrown part of the triangle above the SiO_2 mask is visible (Fig. 2 a)). These dislocations are partly edge (or mixed) type and thus create a "wing tilt". The GaN stripe, grown under unfavorable growth conditions, also shows the presence of stacking faults (SF). As already mentioned, this is a serious problem for the fabrication of high quality non- and semipolar GaN-based devices. The formation of the basal plane stacking faults is mainly visible in the outer regions of the triangle in the area above the mask. This formation is believed to come along with prismatic stacking faults at the starting point of a basal plane SF, with the possibility of decoration with defects such as oxygen. The prismatic and basal plane SF show strong luminescence around 3.3 eV and 3.42 eV, respectively, which is a clear fingerprint of such defects [24]. As will be seen in the next sections concerning CL and PL measurements, we are able to suppress the defect related transitions to a negligible value and therefore the SFs under optimized growth conditions.

3.4 CL

The sample grown under not-optimized growth conditions which was used in the TEM investigations was analyzed by cathodoluminescence measurements. The SFs determined by TEM are found in the outer regions of the overgrown GaN stripes above the mask.

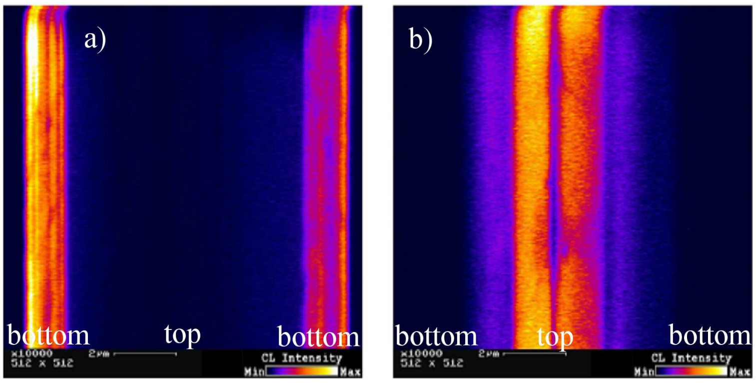

Fig. 3: Monochromatic CL image in top view of a GaN stripe grown under not-optimized growth conditions. a) Image taken from 3.29 eV - 3.33 eV (i.e. defect related). The edges of the image mark the bottom of the triangle. b) Image taken from 3.46 eV - 3.49 eV (i.e. band gap related). The vertical dark line marks the top of the triangle. The highest intensity originates from the area above the mask opening.

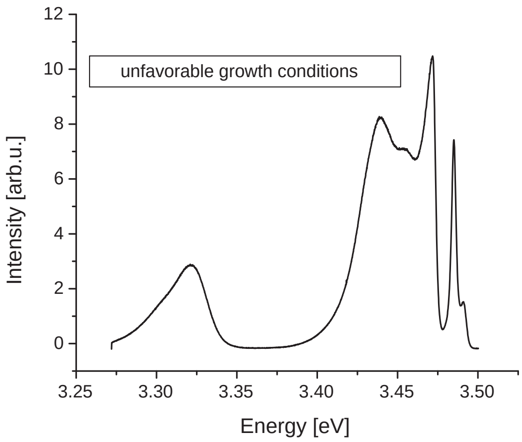

Fig. 4: PL spectrum at 13 K of several GaN stripes grown under unfavorable growth conditions. Defect-related transitions are obvious at 3.3 ev and 3.42 eV.

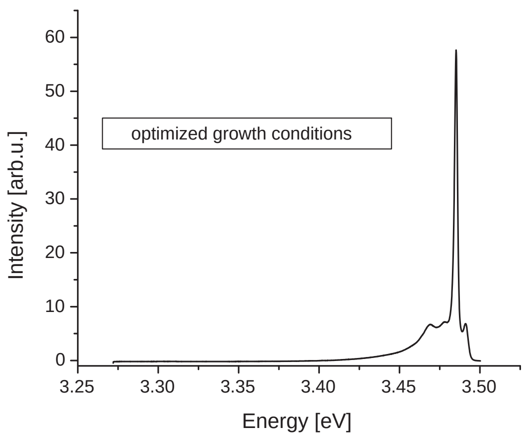

Fig. 5: PL spectrum at 13 K of several GaN stripes grown under optimized growth conditions. No defect-related transitions are obvious.

They can be correlated to strong luminescence peaks around 3.3 eV and 3.42 eV [21, 22]. CL line scans along a triangle facet as well as monochromatic CL images from a top view onto the stripe reveal that the 3.3 eV and 3.42 eV emission (not shown here) originate from the lower part of the triangles, while the band gap related emission is found on the top area (Fig. 3 a) and b)).

3.5 PL

As another tool for the investigation of the material quality photoluminescence measurements have been performed. A He-Cd laser emitting at 325 nm was used as the excitation source with a beam spot diameter of about 100 μm. Therefore several GaN stripes as well as the GaN template are excited at the same time. In Fig. 4 the PL spectrum of the sample described above is shown. This sample, grown under not-optimized growth conditions, shows again strong luminescence peaks around 3.3 eV and 3.42 eV. As already seen in the TEM and CL investigations, these transitions can be ascribed to prismatic and basal plane SF.

The V / III ratio was found to be a critical parameter for the GaN stripe growth. Fig. 5 shows the PL spectrum of a sample grown under optimized growth conditions. As can be seen, the defect-related transitions can be suppressed to a negligible value. I.e. the formation of defects that are responsible for this strong luminescence can be prevented. Thus, it is shown that high quality semipolar GaN can be grown via selective epitaxy and should open the possibility for high performance devices.

4. Optimization of Green QW Emission

The problem of current commercially available (Al,In,Ga)N LEDs is the reduced efficiency for an increasing operation wavelength. Besides the influence of the high internal fields which reduce the recombination propability, the material quality degrades for longer wavelength. It is still a challenge to grow high quality $\mathrm{Ga_{1-x}In_xN}$ alloys with a high indium concentration. The differences in the thermodynamic properties of GaN and InN as well as the high strain which is induced due to the different lattice constants lead to the inferior material quality.

With non- and semipolar GaN one can overcome or at least reduce the influence of the high piezoelectric fields in the QWs, but for a long emission wavelength a high indium content is still needed. Due to the reduced QCSE in non- and semipolar materials an even higher In fraction is necessary to achieve the same wavelength compared to *c*-plane growth. The following sections concentrate on the question whether the semipolar $\{1\bar{1}01\}$ facet is a suitable choice for highly efficient light emitters in the green spectral range.

4.1 In incorporation efficiency

Due to the reduced QCSE on the semipolar facet a nominally similar QW as grown on *c*-plane GaN yields a blue-shifted emission. To compensate this effect, thicker QWs or a higher In fraction is required. To determine the In incorporation efficiency on our semipolar $\{1\bar{1}01\}$-plane an about 50 nm thick GaInN layer was deposited on the facet sidewalls of the triangles. In the same run a *c*-plane reference sample was grown. It can bee assumed that the layers are grown pseudomorphically for both samples as the thickness stays below the critical thickness. HRXRD measurements were performed for the determination of the In content. Fig. 6 shows the $\omega/2\theta$ scan of the (0002) reflection of the *c*-plane reference sample. For the *c*-plane sample an In concentration of 14.6 % was

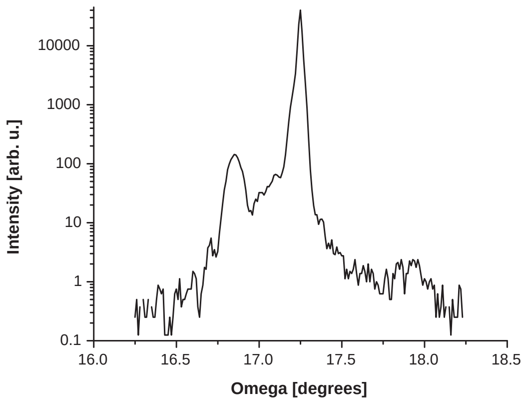

Fig. 6: $\omega/2\theta$-scan of the (0002)-reflection of the polar reference sample

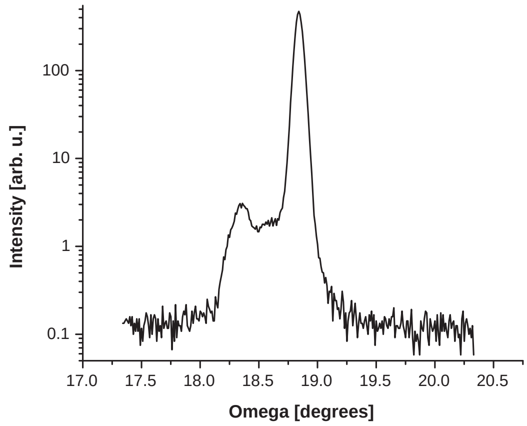

Fig. 7: $\omega/2\theta$-scan of the (1-101)-reflection of the semipolar sample

calculated. In Fig. 7 the $\omega/2\theta$-scan of the (1-101) reflex of the semipolar sample is shown. With respect to the different strain situation on inclined facets an indium concentration as high as 22 % was determined. Although the temperature could be slightly reduced on those side facets compared to *c*-plane growth and therefore increase the indium incorporation, the main reason for the higher In percentage is believed to origin from the different strain situation on the $\{1\bar{1}01\}$-plane. This is another reason why we favor this semipolar GaN plane. The noticeable higher In incorporation should help significantly to achieve longer wavelength emission in spite of the reduced QCSE.

It is worth to mention that the semipolar sample with the thick GaInN layer of about 50 nm shows strong photoluminescence peaking at 2.66 eV at room temperature (not shown). It can be assumed that there is no quantization in such a thick layer. Therefore the transition can be related to the band gap of $In_xGa_{1-x}N$. Thus, the determined In concentration via HRXRD fits well to the luminescence properties of the sample which would predict about 24 % In.

4.2 Optimization of GaInN/GaN MQW growth parameters

For the goal to push the wavelength into the green region, different growth parameters can be changed to achieve a high In incorporation. It is commonly known that low temperature, high In flow and high growth rate are the most promising parameter choices. However, the segregation of the QWs or the formation of metallic indium clusters for QWs containing a high In fraction is a serious problem also for the semipolar $\{1\bar{1}01\}$-plane. Similar to growth experiments for green emission on *c*-plane GaN [25], the best results were achieved with low temperature, high V / III ratio and similar TEGa- und TMIn-precursor flows. Fig. 8 shows the PL spectrum at room temperature for a semipolar GaInN/GaN multiple quantum well (MQW) structure emitting in the green spectral range. For the optimization of the GaInN growth parameters the template as well as the stripes are undoped. The three QWs are capped with an undoped GaN layer with

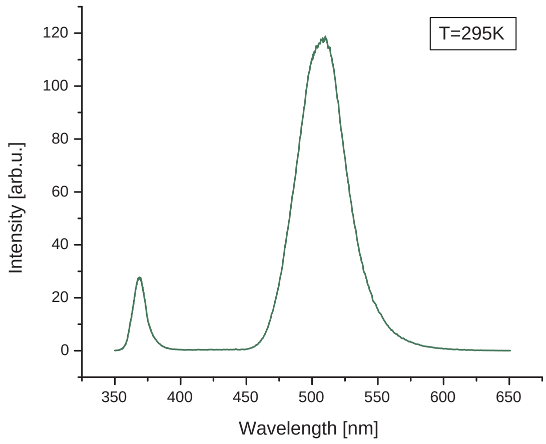

Fig. 8: PL spectrum of a semipolar undoped GaInN/GaN MQW structure showing green emission peaking at 515 nm with a FWHM of 175 meV.

a thickness of about 50 nm. Strong luminescence from the GaInN MQWs can be observed peaking at 515 nm. The relative narrow full width at half maximum (FWHM) of 175 meV @ 295K confirms the good material quality.

4.3 EL characteristics of semipolar LED

In this section EL characteristics of a semipolar LED structure emitting in the bluish-green spectral range are discussed. The growth parameters of this sample are based on an earlier stage of the GaInN/GaN MQW optimization scheme. That's why the emission wavelength is not the same as in the MQW structure described above. For the EL measurements only simple processing steps were applied. There was no mesa etching to define the LED device and for a higher light out coupling efficiency. The p-contacts were defined via standard lithography. Circular In contacts with diameters between 70 µm and 140 µm were used. The EL characteristics were measured on-wafer, collecting the light with an integrating sphere.

Fig. 9 shows the spectrum of such an LED device at a driving current of 100 mA. A FWHM of 215 meV was determined at a wavelength of 495 nm. Optical output powers as high as 240 µW @ 20 mA and 1 mW @ 110 mA have been measured on-wafer. Interestingly, the external efficiency stays nearly constant for the investigated current range (Fig. 10). This is believed to primarily result from the reduction of the piezoelectric field on the semipolar side facets.

5. Conclusion

Semipolar GaInN/GaN LEDs were realized on the $\{1\bar{1}01\}$ side facets of selectively grown GaN stripes with an on-wafer optical output power of 240 µW @ 20 mA and 1 mW @ 110 mA

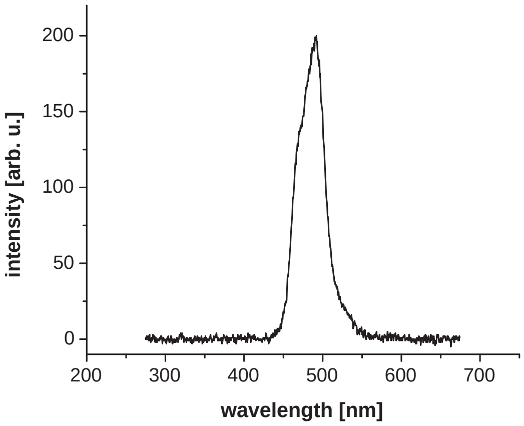

Fig. 9: EL spectrum of a semipolar facet LED at current of 100 mA.

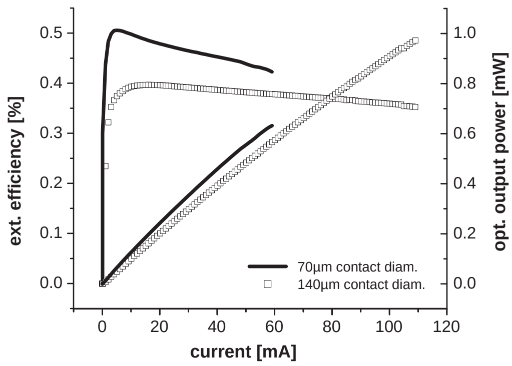

Fig. 10: Optical output power and external efficieny of semipolar facet LED measured at 495 nm emission wavelength for a p-contact diameter of 70 µm and 140 µm.

for about 500 nm. The good material quality was confirmed by a HRXRD rocking curve FWHM for the $(1\bar{1}.1)$ reflection of 185 arcsec and a AFM rms value of 0.25 nm. Defect-related luminescence peaks in CL and PL at 3.3 eV and 3.42 eV could be related to prismatic and basal plane SFs for samples grown under unfavorable growth conditions and could be suppressed completely by optimizing them. Furthermore, a 50 % higher indium incorporation for these $\{1\bar{1}01\}$ facets in comparison to *c*-plane growth is found, what helps significantly to achieve longer wavelength emission in spite of the reduced QCSE.

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