

# Bluish-green semipolar GaInN/GaN light emitting diodes on {1 $\bar{1}$ 01} GaN side facets

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non- and semipolar GaN, could be eliminated in our facet LEDs by optimized growth conditions. Furthermore, a 50 % higher indium incorporation for these {1 $\bar{1}$ 01} facets compared to *c*-plane growth is found, what helps significantly to achieve longer wavelength emission in spite of the reduced Quantum Confined Stark Effect.

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Bluish-green semipolar GaInN/GaN light emitting diodes were realized on the  $\{1\bar{1}01\}$  side facets of selectively grown GaN stripes with an on-wafer optical output power of  $240 \mu\text{W}$  @ 20 mA for about 500 nm emission wavelength. Structural investigations using TEM, SEM, HRXRD and AFM could be related to the luminescence properties in PL and CL. The defect-related luminescence peaks at 3.3 eV and 3.41 eV, typically observed in

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**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 these negative effects on the luminescence efficiency, it is highly desirable to grow GaInN/GaN heterostructures with reduced or completely without 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<sub>2</sub> [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- and semipolar GaN [7–9]. But those results are based on only small GaN pieces in the size of  $3 \times (15\text{--}25) \text{ mm}^2$  [8] which were sliced from high quality *c*-plane GaN grown by HVPE. Those substrates provide a very low threading dislocation and stacking fault density [9], but their costs are prohibitively high for any commercial application [10].

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 [11–15]. Depending on the stripe orientation and growth conditions, different crys-

tal facets can be achieved with reduced or even vanishing polarization fields. This could be verified in different studies [12, 14, 16, 17].

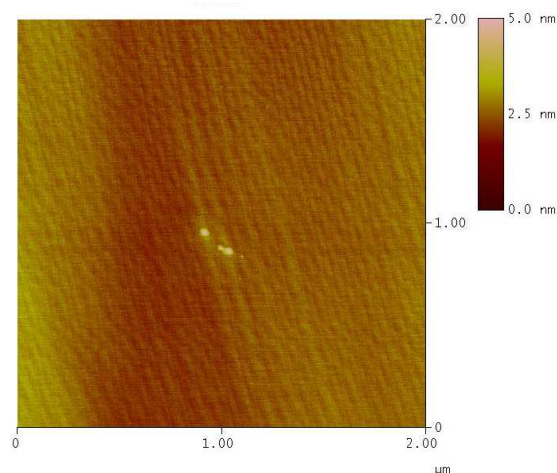
GaN material quality and complete semipolar LED structures grown by selective epitaxy. Structural properties using high resolution X-ray diffraction (HRXRD), atomic force microscopy (AFM) and transmission electron microscopy (TEM) can be correlated to characteristics in photo- and cathodoluminescence (PL, CL). Besides results of electroluminescence (EL) measurements are presented for a device emitting in the bluish-green spectral range.

**2 Experimental** The samples, pure GaN stripes and complete LED structures, were grown by low pressure metalorganic vapor phase epitaxy (MOVPE). First, about 2  $\mu\text{m}$  thick, high quality GaN templates were grown on *c*-plane sapphire [18]. These were subsequently structured using SiO<sub>2</sub> stripes oriented along the  $\langle 11\bar{2}0 \rangle$  direction. The parameters of the second epitaxial step have been tailored to grow triangularly shaped GaN stripes in the several  $\mu\text{m}$  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 Al-GaN electron barrier and a GaN:Mg top layer. The nominal thickness of the GaInN QWs and the GaN barriers was determined to be about 7 nm and 10 nm, respectively. Further information on the growth and processing can be found elsewhere [14].

For the investigation of the structural properties, different measurement methods like high resolution x-ray diffraction (HRXRD), atomic force microscopy (AFM) and transmission electron microscopy (TEM) have been performed. The results could be correlated to luminescence characteristics using photo- and cathodoluminescence (PL, CL). Besides, electroluminescence (EL) measurements were carried out for the LED samples emitting in the bluish-green spectral range.

**3 Results and discussion** First, HRXRD investigations have been performed determining the crystal material quality of the GaN stripes. A broad beam spot of several mm<sup>2</sup> was used as an excitation source. Thus, the detected signal resulted as an integration over several stripes. However, the rocking curve of the  $(1\bar{1}.1)$  reflection showed a relative 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.

Furthermore, the good material quality is confirmed performing 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 oriente the semipolar facet horizontally, exposing the surface to the top. The 2  $\mu\text{m}$  x 2  $\mu\text{m}$  scan shows a smooth surface with a rms value as low as 0.25 nm. This result confirms the advantage of the naturally stable



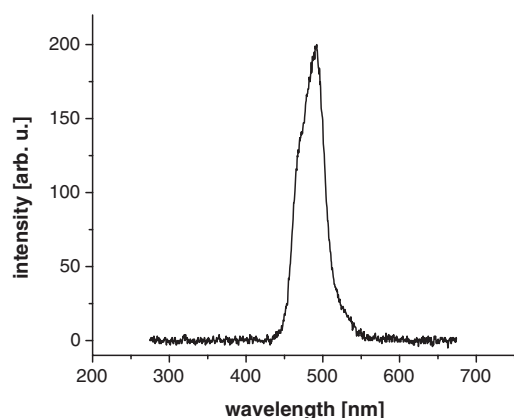
**Figure 1** 2  $\mu\text{m}$  x 2  $\mu\text{m}$  AFM scan of the semipolar  $\{1\bar{1}01\}$  side facet of a LED structure. Determined rms value of 0.25 nm.

surface and is one reason why the  $\{1\bar{1}01\}$  plane is believed to be one of the favorable semipolar GaN planes.

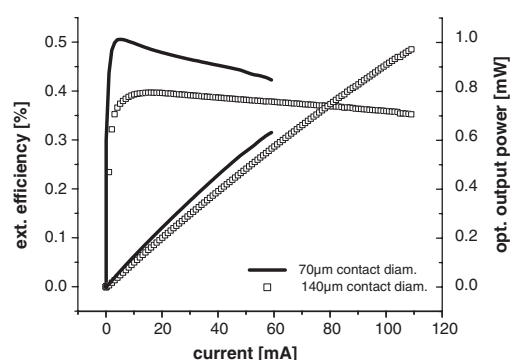
With respect to the defect situation in such a GaN stripe, TEM investigations have been carried out. Otherwise than naively expected, the present defects are not only the result of threading dislocations originating from the template. Under unfavorable growth conditions, the formation of basal plane and prismatic stacking faults (SFs) is clearly visible, further evidenced by luminescence peaks at 3.3 eV and 3.41 eV [21], which are a clear fingerprint of such defects [22]. Such stacking faults are a common problem in the field of non- and semipolar GaN fabrication [19, 20], but could be depressed to a negligible value in our stripes under optimized growth conditions. More details to the TEM investigations and the reduction of SFs will be published elsewhere.

Although the reduced QCSE potentially leads to much better quantum efficiencies in longer wavelength light emitting devices, more indium is needed in the active QWs in comparison to *c*-plane growth due to the reduced QCSE caused band gap shift. Fortunately, we indeed found a 50% higher In incorporation on our semipolar  $\{1\bar{1}01\}$  planes compared to *c*-plane growth as determined by HRXRD measurements in combination with a sophisticated model taking the different strain behavior for the different planes into account. This trend was predicted by Northrup et al. [23] and this is another reason why we favor this semipolar GaN plane.

Combining these findings, semipolar LED structures were fabricated on the side facets of the selectively grown GaN stripes with an emission wavelength of nearly 500 nm. Fig. 2 shows the spectrum of such a LED device at a driving current of 100 mA. Using only simple, circular In contacts with diameters between 70  $\mu\text{m}$  and 140  $\mu\text{m}$  and no further processing steps like mesa etching, mounting or encapsulation, on-wafer optical output powers as high



**Figure 2** EL spectrum of a semipolar facet LED at current of 100 mA.



**Figure 3** Optical output power and external efficiency of semipolar facet LED measured at 495 nm emission wavelength.

as  $240 \mu\text{W}$  @ 20 mA have been measured. Interestingly, the external efficiency stays nearly constant for the investigated current range (Fig. 3). This is believed to primarily result from the reduction of the piezoelectric field on the semipolar side facets.

**4 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  $240 \mu\text{W}$  @ 20 mA for about 500 nm. The good material quality was confirmed by a HRXRD rocking curve 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 3.41 eV could be related to prismatic and basal plane SFs and suppressed by optimized growth conditions. 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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