3D GaN Structures with Reduced Piezoelectric Fields For Efficient Quantum Well Emission

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A fabrication method for the formation of 3D GaN structures with reduced piezoelectric field is presented. Via optimized selective epitaxy the surface is just composed of hexagonally patterned semipolar $\{1\bar{1}01\}$ *or* $\{11\bar{2}2\}$ *planes. GaN growth with less* NH_3 *at a higher growth speed, a doubled effective area and good light outcoupling properties compared to c-plane growth are additional advantages of this effective technique. The high material quality is confirmed via PL and CL measurements (FWHM of* D^0X*: 2.6 meV). No defect related optical transitions, often observed in non- and semipolar GaN, were found. An InGaN QW grown on these semipolar planes showed efficient green (522 nm) light emission in spite of a reduced influence of the quantum confined Stark effect (QCSE).*

1. Introduction

In recent years, much attention has been paid to group III-nitrides due to their properties suited for the fabrication of efficient optoelectronic devices. High-performance InGaN/GaN based light emitting diodes (LEDs) with an emission wavelength in the blue/violet spectral region or in combination with phosphors for white light sources are commercially available nowadays [1]. However, for longer wavelengths the efficiency of those devices grown in the commonly used c-direction of GaN is continuously decreasing with increasing indium content in the active region [2]. This fact is thought to be in large part caused by strong built-in electrical fields as a result of the biaxially compressively stressed InGaN QWs. Those piezoelectric fields lead to a local separation of electrons and holes within the quantum wells (QWs) and consequently to less efficient device structures due to a reduced overlap of electron and hole wave functions.

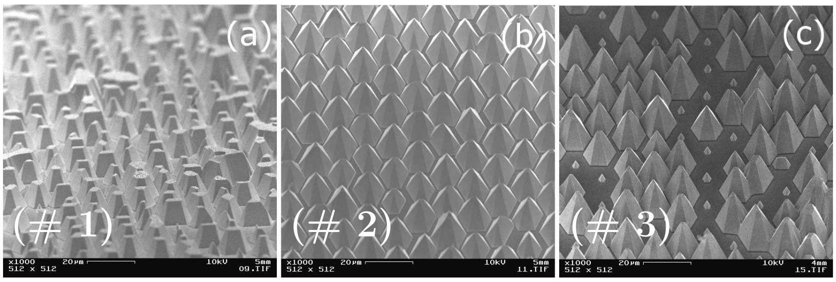

Fig. 1: Bird's eye view of normal pyramids grown with $f_{\mathrm{TMGa}} = 51\,\mu\mathrm{mol/min}$ (a), $f_{\mathrm{TMGa}} = 102\,\mu\mathrm{mol/min}$ (b), and $f_{\mathrm{TMGa}} = 153\,\mu\mathrm{mol/min}$ (c).

By suppressing these strong piezoelectric fields it is expected that the efficiency of nitride-based devices can be drastically improved. That is the reason why many groups are currently dealing with the investigation of GaN and GaN-based devices in non- and semipolar growth directions, as it could be demonstrated experimentally that the piezoelectric fields are reduced for QWs grown along these crystal directions [3].

Nevertheless, the competition between material quality and sample size is still limiting the use of non- or semipolar material for industrial production. On the one hand on foreign substrates with a conventional size just inferior material quality compared to c-plane growth can be achieved up to now. Non-radiative recombination is then compensating the advantage of the reduced fields and leads to the bad performance of such devices [4,5]. On the other hand high quality material of non- and semipolar GaN can be obtained by cutting small pieces from c-plane grown HVPE GaN. Those substrates provide a very low threading dislocation and stacking fault density which seem to be the key factors for the remarkable device performance [6, 7]. However, the sample size in the range of 3 x 20 mm^2 [7] and its high price are still limiting factors for any mass production [8].

In this study we present a method for the fabrication of semipolar GaN planes with high material quality and the possibility for large area production. Selective epitaxy is used to grow three dimensional (3D) GaN structures providing semipolar $\{1\bar{1}01\}$ and $\{11\bar{2}2\}$ GaN surfaces in hexagonal patterns. By optimized growth conditions for the second epitaxial step the surface is just composed of semipolar planes with reduced piezoelectric fields which are useful for efficient light emitters.

2. Experimental

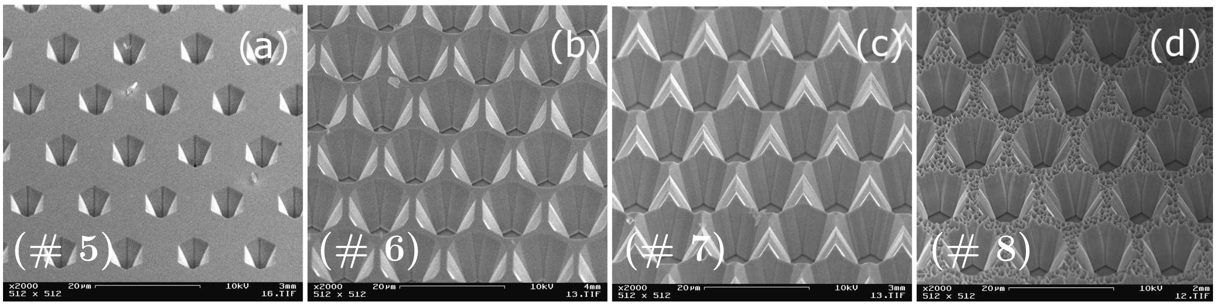

Fig. 2: 45° view on inverse pyramids (3 μm opening, 10 μm mask) grown at $T = 1120°C$ (a), 1060°C (b), 950°C (c), and 850°C (d).

The samples were grown by low pressure metalorganic vapor phase epitaxy (MOVPE) using trimethylgallium (TMGa), triethylgallium (TEGa), trimethylindium (TMIn), and ammonia (NH_3) as precursors. First, about 2 μm thick high quality GaN templates were fabricated. The well known and established c-plane growth was performed on c-plane sapphire substrates including an in-situ SiN interlayer for efficient defect reduction [9]. After the deposition of 200 nm SiO_2 mask material via plasma enhanced chemical vapor

Table 1: Growth parameters of different samples

sample no.	T [°C]	f_{TMGa} [µmol/min]	f_{NH3} [mmol/min]	p [hPa]
# 1	1120	51	90	150
# 2	1120	102	90	150
# 3	1120	153	90	150
# 4	1120	102	90	250
# 5	1120	102	45	150
# 6	1060	102	45	150
# 7	950	102	45	150
# 8	850	102	45	150

deposition (PECVD) different hexagonally shaped patterns were formed using standard photolithography and reactive ion etching (RIE).

One part of the test pattern consists of hexagonal openings (3 µm), whereas the masked areas were fixed to a width of 3 µm and 10 µm. This design allows the formation of ordered pyramids with $\{1\bar{1}01\}$ facets (in the following text called 'normal'), similar to the epitaxial lateral overgrowth (ELOG) technique that is normally used for defect reduction in GaN growth, see e.g. [10]. The counterpart of the mask pattern consists of hexagonal masked areas surrounded by open stripes with a width of 3 µm. The diameter of the masked areas is set to 3 µm and 10 µm. This pattern allows the growth of inverse pyramids where predominantly $\{11\bar{2}2\}$ facets are formed (in the following text called 'inverse'). The formation of normal and inverse pyramids can be understood by the different growth speed in a- and m-direction. The growth in $\langle 11\bar{2}0\rangle$-direction is found to be faster than in $\langle 1\bar{1}00\rangle$-direction. That is the reason why one can find $\{1\bar{1}0x\}$ facets (normal pyramids) if the mask is designed for divergenting growth and $\{11\bar{2}x\}$ facets for convergenting growth (inverse pyramids).

In order to achieve homogeneously distributed structures in combination with a high material quality and good optical properties, systematic variations of the GaN growth parameters were investigated in the second epitaxial step. On top of these structures an InGaN single quantum well (SQW) was grown and then capped with undoped GaN. The properties of the QW emission act as a direct monitor for the semipolar InGaN/GaN material quality. Whereas the QW emission for the first series had a moderate wavelength of about 470 nm it was pushed into the green spectral region after the optimization of the underlayer 3D semipolar GaN structures. Up to 522 nm were measured by adjusting the growth parameters of the active region.

For the study of the structural and optical properties optical and scanning electron microscopy (SEM) investigations were performed, combined with photoluminescence (PL) and locally resolved cathodoluminescence (SEM-CL) measurements.

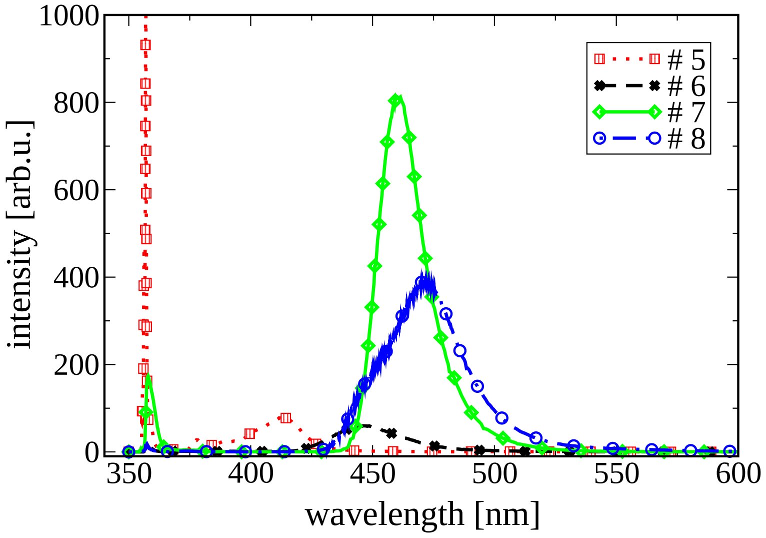

Fig. 3: PL measurement of inverse pyramids (3 µm opening, 10 µm mask) grown at $T = 1120°\mathrm{C}$ (# 5), 1060°C (# 6), 950°C (# 7), and 850°C (# 8).

3. Results and Discussion

First, our standard c-plane GaN growth parameters applied to the masked template (sample # 1, see table 1). Fig. 1(a) shows the resulting structures of an area where normal pyramids are expected. As can be seen 3D structures developed, but their distribution is inhomogenious and no distinct facet type is dominating. On areas where inverse pyramids are expected just a completely closed layer was found for all geometries. Obviously, our standard growth conditions are not applicable for the formation of 3D structures with semipolar surfaces. Different parameters are well known to reduce the lateral (2D) and force the vertical (3D) growth mode: A low V/III ratio, a low growth temperature, and a high reactor pressure. In sample # 2 the V/III ratio was lowered by a doubled TMGa flow. The normal pyramids are now well ordered and developed $\{1\bar{1}01\}$ facets as the most stable surface (see Fig. 1(b)). The symmetry of each pyramid is good but not perfect. At the relatively sharp apex of the pyramids defect formation is visible. By further increasing the TMGa flow to $f_{\mathrm{TMGa}} = 153\,\mu\mathrm{mol/min}$ (sample # 3) following situation can be recognized (see Fig. 1(c)): Besides well ordered structures similar to sample # 2 stochastically distributed areas can be found with pyramids just as big as the mask opening (3 µm). Similar behavior was found for sample # 5 with a TMGa flow of $f_{\mathrm{TMGa}} = 102\,\mu\mathrm{mol/min}$, but with reduced NH_3 of $f_{\mathrm{NH3}} = 45\,\mathrm{mmol/min}$ (not shown). Obviously a too low V/III leads to a inhomogenious growth for the individually growing pyramids.

Looking to the results of the PL measurements performed for sample # 1 to # 3, also # 2 is favored due to the highest intensity and the longest wavelength for the QW emission (not shown).

Based on # 2 the reactor pressure is now increased to $p = 250\,\mathrm{hPa}$ in sample # 4 to further enhance the 3D growth mode. But because the PL intensity was reduced and no big changes in the pyramids' shape could be observed (not shown), the pressure was kept

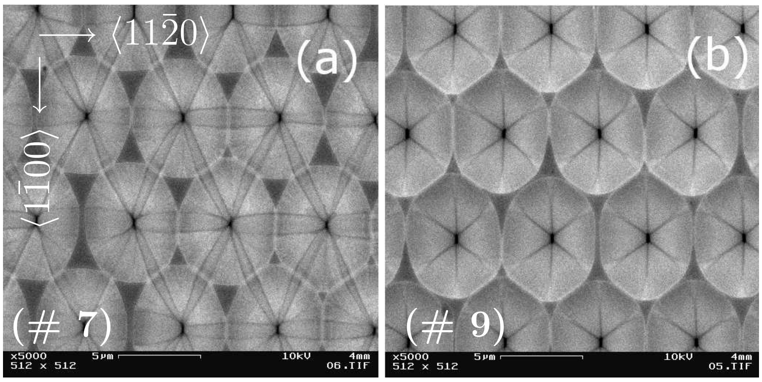

Fig. 4: Top view on inverse pyramids (3 μm opening, 3 μm mask) grown without (a) and with (b) smoothing step.

at $p = 150\,\text{mbar}$ for the following experiments.

As already mentioned, sample # 5 was grown with a reduced NH_3 of $f_{\text{NH3}} = 45\,\text{mmol/min}$. Although this low V/III ratio (at high growth temperature) is not favored for the growth of normal individually grown pyramids due to their inhomogenious distribution, the optical properties of the GaN as well as of the InGaN QWs grown on the inverse pyramids were drastically improved. This is the reason why in the following temperature series the V/III ratio was kept as in # 5.

Based on sample # 5 ($T = 1120°\text{C}$) the reactor temperature during the GaN growth was gradually reduced. The temperature was set to $T = 1060°\text{C}$ (# 6), $T = 950°\text{C}$ (# 7) and $T = 850°\text{C}$ (# 8). Due to the fact that inverse pyramids show a stronger influence on these changes and their homogeneity is basically better, we concentrate on them in the following investigations. Fig. 2 shows the SEM pictures of inverse pyramids with a mask width of 10 μm for this temperature series. The c-plane surface which is present on a big area in sample # 5 is strongly reduced in # 6 and almost vanished in # 7. When the temperature was further reduced to $T = 850°\text{C}$ a rough c-plane surface is observed. Under these conditions the temperature is too low for defect-free growth. Hence, the favored temperature is set to $T = 950°\text{C}$. PL measurements also confirm this trend. Sample # 7 shows the best QW emission for inverse as well as for normal grown pyramids (Fig. 3).

Having a closer look to the geometrical properties of the inverse pyramids of # 7 (Fig. 2(c)), besides six rectangular shaped $\{11\bar{2}2\}$ facets one can also find six triangular shaped $\{1\bar{1}01\}$-facets. These properties also exist for the small mask geometry, (Fig. 4(a)). In this case two distinct QW peaks can be observed in PL measurements (Fig. 5). Determined by SEM-cathodoluminescence the two peaks can exclusively be assigned to the two facet types where the $\{1\bar{1}01\}$ facets show the longer emission (not shown). This fact leads to an additional step in the growth procedure. By ramping the temperature up to $T = 1120°\text{C}$ prior to the QW growth (# 9) a smoothing of the surface is desired. As can be seen in Fig. 4(b) this step is helpful to force the $\{11\bar{2}2\}$ facets and minimize its counterpart which were even dominating previously. Hence, the PL QW emission just shows one transition

(Fig. 5).

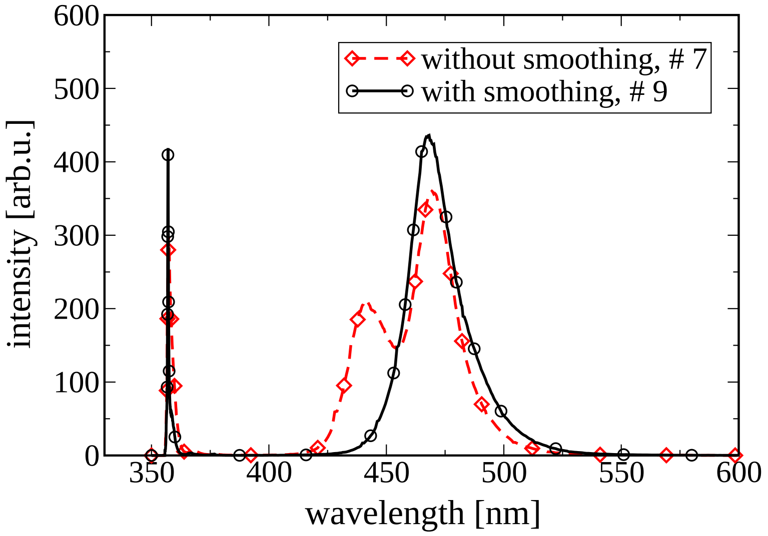

Fig. 5: PL measurement of inverse pyramids (3 µm opening, 3 µm mask) grown with (# 9) and without (# 7) smoothing step.

Sample # 9 is now the base for pushing the QW emission into the green region. Due to the reduced piezoelectric field on the semipolar planes the influence of the quantum confined Stark effect (QCSE) is also reduced. Consequently, for the same wavelength more indium and/or thicker QWs are needed in comparison to c-plane growth. Adjusting the growth parameters of the active region to an In incorporation of about 30 %, efficient green (522 nm) QW emission could be realized on semipolar pyramids. In Fig. 6 the PL spectra of inverse pyramids with the small geometry (see Fig. 4(b)) of sample # 10 are depicted. At $T = 14$ K unstained GaN related transitions are observed without any hint for defect related transitions, as often observed from non- and semipolar grown GaN [11]. Furthermore, the slight drop of the QW intensity at $T = 295$ K gives evidence for a high internal quantum efficiency (IQE).

4. Conclusion

We presented a fabrication method for the formation of 3D GaN planes with reduced piezoelectric field. The 3D structures double the effective area, provide semipolar surfaces and allow good light outcoupling. Additionally, the low NH_3 at high growth speed can reduce fabrication costs. Efficient green (522 nm) QW emission on these structures could be demonstrated.

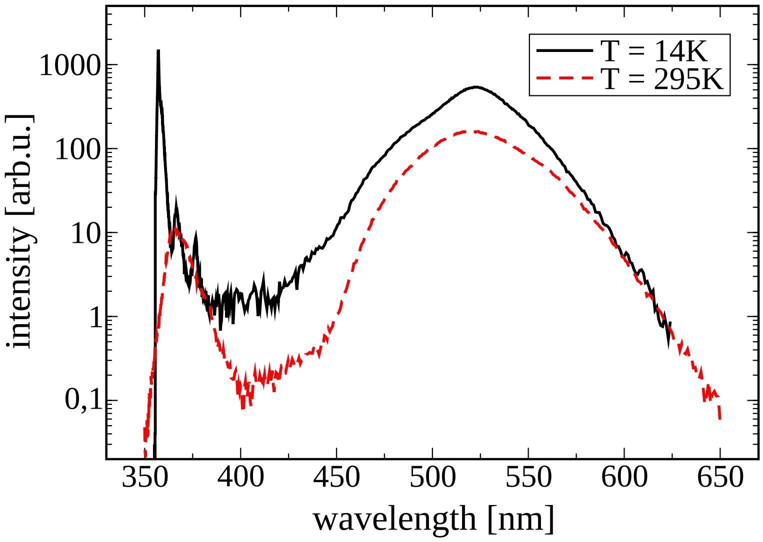

Fig. 6: PL measurement of inverse pyramids (3 µm opening, 3 µm mask) with long emission wavelength (# 10) at $T = 14\,\mathrm{K}$ and $T = 295\,\mathrm{K}$.

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