Galliumnitride Nanostripes with Semipolar Quantum Wells for LED and Laser Applications

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We present LEDs and asymmetric waveguide structures with embedded nanostripes and semipolar $\{10\bar{1}1\}$ *quantum wells. All samples are based on c-plane GaN/AlGaN templates grown heteroepitaxially on c-plane sapphire substrates by metal organic vapour phase epitaxy. The nanostripes have a periodicity of 250 nm and were achieved by selective area epitaxy with dielectric growth masks structured on full 2-inch wafers. After quantum well growth on the semipolar crystal facets of the nanostripes, they are completely embedded, resulting in a flat c-plane surface. This allows conventional device processing to be applied. Structural, optical, and electrical characterization has been performed.*

1. Introduction

Research in semipolar GaN crystal planes for efficient green light emitters is still ongoing [1, 2]. Best results have been achieved based on free-standing GaN templates and homoepitaxial approaches [3–6]. These commercially available, semipolar GaN quasi-substrates are high in cost and small in size. Consequently, heteroepitaxy of semipolar GaN based on cheap sapphire substrates maintains interest [7]. We pursue one of these heteroepitaxial approaches, i.e. the selective growth of 3D structures with semipolar surfaces which is based on growth in c-direction. Thus, it can be realized on cheap and also large foreign substrates, i.e. sapphire. Already, a high crystal quality has been achieved despite heteroepitaxy [8]. LEDs with semipolar QWs based on micrometer sized 3D structures have been reported [9,10]. Yet, these 3D topologies require specially adapted device processing. Our aim is therefore to maintain a plane surface, where established structuring methods for contacts, resonator formation etc. can be applied. We reduce the size of

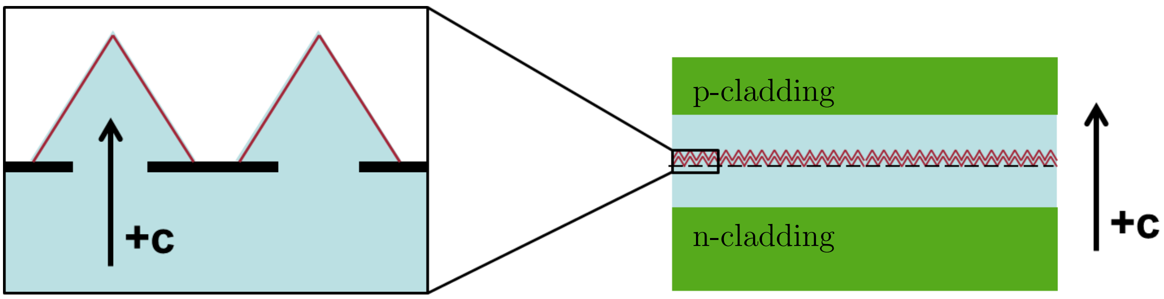

Fig. 1: Reduction of size of 3D GaN will allow embedding of semipolar QWs within conventional c-oriented layers.

the 3D structures in order to use them exclusively within the active region of our aspired devices. This miniaturization allows subsequent planarization (see Fig. 1). All dimensions must be restricted to a few hundred nanometers, beyond the limitations of conventional optical lithography. Previously, we have reported on nanostructuring for selective area epitaxy based on laser interference lithography (LIL) for LED [11] and photonic crystal applications [12]. However, the LIL samples still suffered from mask irregularities and the structured area was limited to some cm^2, which is why an alternative structuring method was used as described in the following.

2. Experimental

The samples are grown in an Aixtron-200/4RF-S HT MOVPE reactor with standard precursors TMAl, TMGa, TMIn and high purity ammonia. Silane and Cp_2Mg are used for n- and p-doping, respectively; Pd diffused hydrogen and high purity nitrogen are used as carrier gases. First, c-oriented GaN/AlGaN templates of about 3.5 µm thickness are grown on c-plane sapphire with conventional growth conditions. An oxygen doped AlN nucleation layer as well as an in-situ deposited SiN interlayer are employed for defect reduction [13]. The top 1.8 µm are silicon-doped to achieve a nominal doping level of $3.5 \times 10^{18} cm^{-3}$. The templates include a 0.4 µm thick $Al_{0.1}Ga_{0.9}N$ as bottom waveguide cladding and are capped with 30 nm GaN. Afterwards, 30 nm SiN_x is deposited by PECVD as growth mask. Upon this dielectric mask, a very thin (below 100 nm) layer of resist is structured by nanoimprint lithography [2]. Dry etching with SF_6, results in stripes aligned parallel to the a-direction of GaN with a period of 250 nm over the full 2-inch wafer. Afterwards, any remaining resist is removed by an O_2-plasma treatment and the samples are cleaned with a mixture of H_2O_2 and H_2SO_4 and an aqueous KOH solution, before being reloaded into the MOVPE reactor. GaN stripes with a triangular cross section and $\{10\bar{1}1\}$ side facets are grown at 950 °C for 110 s with a V/III ratio of 260. An InGaN pre-well of 50 nm thickness with 5% In is deposited on top of the stripes, in order to reduce the strain gradient and increase the confinement. An InGaN quantum well is grown at 750 °C to 770 °C to achieve an emission wavelength of 420 nm to 460 nm. After an undoped spacer, the stripes are embedded with a Mg-doped layer at 1080 °C with a V/III ratio of 1080 resulting in a planar surface. At this point, the structure includes neither an electron blocking layer nor multiple quantum wells common to c-plane LEDs. The fully planarized laser structures were investigated by transmission electron microscopy (TEM) and scanning transmission electron microscopy (STEM) at the central electron microscopy facility of Ulm University for structural defects. The embedding with doped GaN allows electrical pumping of the semipolar QWs. For electrical characterization, the samples were annealed in an ambient atmosphere at 750 °C for 60 s to activate the Mg-acceptors. Indium contacts were evaporated onto the p-side of the LED. The contacts had diameters ranging from 70 µm to 140 µm and were 1 µm thick. Measurements were taken inside an integrating sphere and P-I as well as I-V curves were recorded.

[2] Carried out by J. Harming of the EV Group E. Thallner GmbH

3. Results

We achieved homogeneous growth of sub-micrometer sized stripes aligned along $< 11\bar{2}0 >$ over the complete sample area enabling subsequent embedding. Mg doping enhances the lateral growth [14] and facilitates the planarization of the device. Yet, the stability of the $\{10\bar{1}1\}$ facets [15] requires relatively long overgrowth times (equivalent to 180 nm layer thickness) compared to typical c-plane LED p-type layers.

3.1 Structural analysis

Figure 2 shows both weak-beam dark-field and bright-field TEM images of a sample cross-section from sapphire to surface highlighting threading dislocations (TDs). The effective defect reduction by the in-situ SiN_x interlayer is clearly visible. Only few dislocations penetrate and go on to the surface and we find no indication that new dislocations are created at the interfaces, affecting the semipolar quantum wells. Additionally, almost no

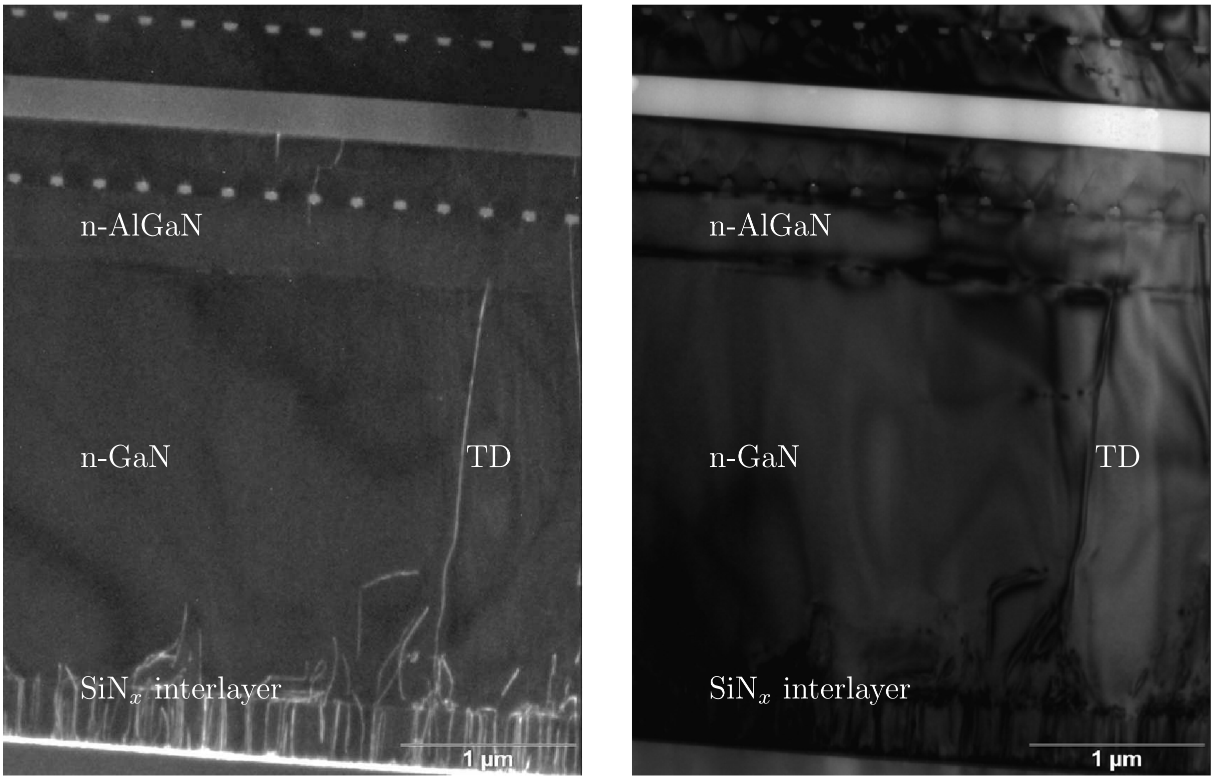

Fig. 2: Weak-beam dark-field (left) and bright-field (right) TEM image. TDs are stopped by the in-situ SiN_x mask. The active zone within the waveguide structure and the semipolar QWs are almost defect-free.

stacking faults (SFs) are found which often affect semipolar QWs. Figure 3 shows a high-angle annular dark field (HAADF)STEM image of the upper region, providing excellent Z-contrast; the AlGaN waveguide cladding is clearly visible and with very few defects present. The SiN_x mask exhibits a homogeneity of a few nanometers. A more detailed look (Fig. 4) shows the homogeneity of the semipolar QW on the stripes. The thickness of the single QW stays constant and has only slight variation. This is a huge improvement compared to previous results [11] where mask irregularities resulted in distorted quantum wells.

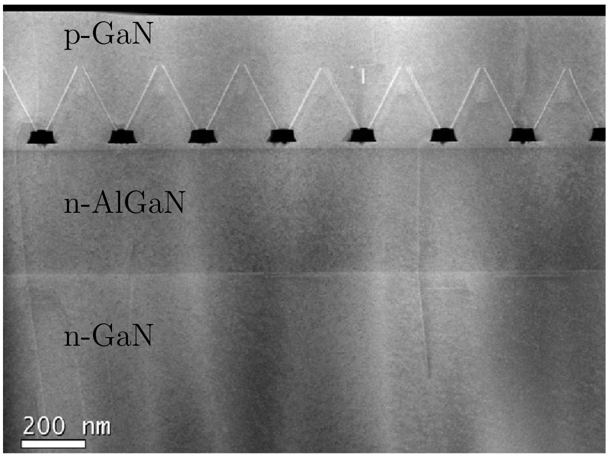

Fig. 3: HAADF STEM image of the waveguide region. Some TDs penetrate, but almost no SFs are found.

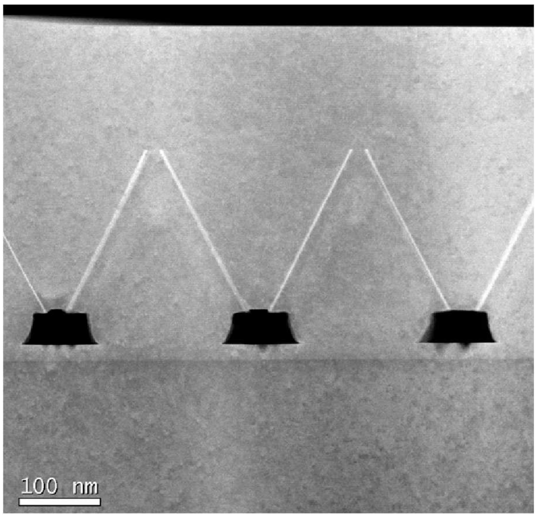

Fig. 4: HAADF STEM image of two triangular stripes. The QWs show very little thickness variance along the facet.

3.2 Electrical characterization

The laser structures include a fully functional p-n junction, so testing in LED mode is easily available. They were activated for 1 minute at 750 °C in ambient atmosphere before In contacts were deposited for on-wafer testing. Figure 5 shows the power-current-voltage characteristics of a laser structure in LED operation under cw-conditions. The emission wavelength is 430 nm with a FWHM of 130 meV (spectra not shown).

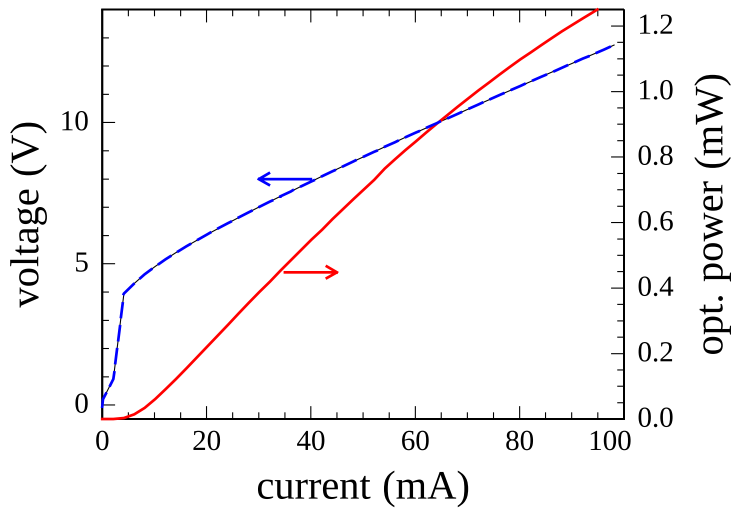

Fig. 5: P-I-V characteristics of laser structure with GaN nanostructures under LED operation.

4. Conclusion

We have fabricated GaN based LEDs with GaN nanostripes and semipolar QWs embedded within a waveguide structure on 2-inch c-oriented sapphire substrates. Analysis by TEM and STEM shows that our nanoimprint structuring results in highly homogeneous and high quality semipolar quantum wells which are completely embedded. On-wafer testing in LED operation produced electroluminescence over 1 mW output power.

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References

[1] H. Ohta, S.P. DenBaars, and S. Nakamura, "Future of group-III nitride semiconductor green laser diodes", *J. Opt. Soc. Am. B*, vol. 27, pp. B45–B49, 2010.

[2] M.T. Hardy, D.F. Feezell, S.P. DenBaars, and S. Nakamura, "Group III-nitride lasers: a materials perspective", *Materials Today*, vol. 14, pp. 408–415, 2011.

[3] Y. Enya, Y. Yoshizumi, T. Kyono, K. Akita, M. Ueno, M. Adachi, T. Sumitomo, S. Tokuyama, T. Ikegami, K. Katayama, and T. Nakamura, "531 nm green lasing of InGaN based laser diodes on semi-polar $\{20\bar{2}1\}$ free-standing GaN substrates", *Appl. Phys. Express*, vol. 2, pp. 082101-1–3, 2009.

[4] M. Adachi, Y. Yoshizumi, Y. Enya, T. Kyono, T. Sumitomo, S. Tokuyama, S. Takagi, K. Sumiyoshi, N. Saga, T. Ikegami, M. Ueno, K. Katayama, and T. Nakamura, "Low threshold current density InGaN based 520–530 nm green laser diodes on semi-polar $\{20\bar{2}1\}$ free-standing GaN substrates", *Appl. Phys. Express*, vol. 3, pp. 121001-1–3, 2010.

[5] A. Avramescu, T. Lermer, J. Müller, C. Eichler, G. Bruederl, M. Sabathil, S. Lutgen, and U. Strauss, "True green laser diodes at 524 nm with 50 mW continuous wave output power on *c*-plane GaN", *Appl. Phys. Express*, vol. 3, pp. 061003-1–3, 2010.

[6] R.M. Farrell, E.C. Young, F. Wu, S.P. DenBaars, and J.S. Speck, "Materials and growth issues for high-performance nonpolar and semipolar light-emitting devices", *Semicond. Sci. Technol.*, vol. 27, pp. 024001-1–14, 2012.

[7] F. Scholz, "Semipolar GaN grown on foreign substrates: a review", *Semicond. Sci. Technol.*, vol. 27, pp. 024002-1–15, 2012.

[8] T. Wunderer *et al.*, "Three-dimensional GaN for semipolar light emitters", *Phys. Status Solidi B*, vol. 248, pp. 549–560, 2011.

[9] B. Neubert, T. Wunderer, P. Brückner, F. Scholz, M. Feneberg, F. Lipski, M. Schirra, and K. Thonke, "Semipolar GaN/GaInN LEDs with more than 1mW optical output power", *J. Cryst. Growth*, vol. 298, pp. 706–709, 2007.

[10] T. Wunderer, J. Wang, F. Lipski, S. Schwaiger, A. Chuvilin, U. Kaiser, S. Metzner, F. Bertram, J. Christen, S.S. Shirokov, A.E. Yunovich, and F. Scholz, "Semipolar GaInN/GaN light-emitting diodes grown on honeycomb patterned substrates", *Phys. Status Solidi C*, vol. 7, pp. 2140–2143, 2010.

[11] R.A.R. Leute, D. Heinz, J. Wang, F. Lipski, T. Meisch, K. Thonke, J. Thalmair, J. Zweck, and F. Scholz, "GaN based LEDs with semipolar QWs employing embedded sub-micrometer sized selectively grown 3D structures", *J. Cryst. Growth*, vol. 370, pp. 101–104, 2013.

[12] D. Heinz, R.A.R. Leute, S. Kizir, Y. Li, T. Meisch, K. Thonke, and F. Scholz, "Ga(In)N photonic crystal light emitters with semipolar quantum wells", *Jpn. J. Appl. Phys.*, vol. 52, pp. 062101-1–5, 2013.

[13] J. Hertkorn, F. Lipski, P. Brückner, T. Wunderer, S.B. Thapa, F. Scholz, A. Chuvilin, U. Kaiser, M. Beer, and J. Zweck, "Process optimization for the effective reduction of threading dislocations in MOVPE grown GaN using in situ deposited SiN_x masks", *J. Cryst. Growth*, vol. 310, pp. 4867–4870, 2008.

[14] B. Beaumont, S. Haffouz, and P. Gibart, "Magnesium induced changes in the selective growth of GaN by metalorganic vapor phase epitaxy", *Appl. Phys. Lett.*, vol. 72, pp. 921-923, 1998.

[15] Y. Kato, S. Kitamura, K. Hiramatsu, and N. Sawaki, "Selective growth of wurtzite GaN and $Al_xGa_{1-x}N$ on GaN/sapphire substrates by metalorganic vapor phase epitaxy", *J. Cryst. Growth*, vol. 144, pp. 133–140, 1994.