Laser Structures with Semipolar Quantum Wells Grown by Selective Area Epitaxy

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Using selective area epitaxy to produce three-dimensional GaN structures, two different concepts for laser diodes (LDs) with semipolar quantum wells (QWs) are developed, each having distinct advantages and disadvantages. The first approach utilizes a stripe with triangular cross-section not only to grow semipolar quantum wells on, but also as waveguide and resonator cavity. Based on simulations of modal characteristics we develope the epitaxial structure and address the difficulties of selective growth of the aluminum containing layers. The second approach integrates the three-dimensional structures with semipolar sidefacets into a conventional LD design with planar cladding layers. Therefore we miniaturize the selectively grown stripes to a submicrometer scale, positioning the active layer with semipolar QWs inside the core of a planar waveguide. For both approaches we present experimental results, regarding structural as well as optical properties including SEM, CL, PL, TEM and gain measurements.

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 reduced piezoelectric field on these facets promises great advantages of device performance reducing the Quantum Confined Stark Effect (QCSE) and its negative consequences for longer wavelenghts (i.e green) [1]. Additionally, the 3D growth of stripes, pyramids or the like enables us to manipulate the extraction and propagation of light by changing the surface topology. LEDs based on GaN stripes with $\{11\bar{2}2\}$ or $\{10\bar{1}1\}$ facets have been published [2] (see Fig. 1); the selective growth of GaN and the epitaxy of InGaN/GaN QWs is well under control. The fabrication of laser diodes (LDs) based on such three-dimensional structures, however, faces several major challenges due to the more complex device architecture. Particularly, the formation of resonator and waveguide, typically

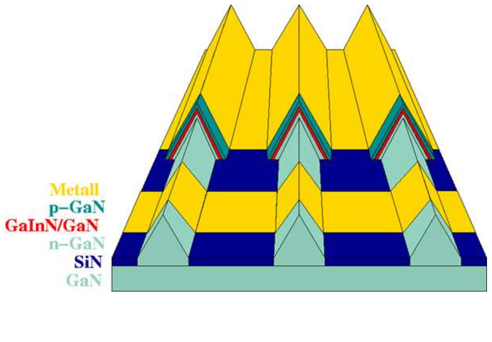

Fig. 1: Realization of a LED with semipolar quantum wells on the sidefacets of GaN stripes with triangular cross-section.

realized by AlGaN/GaN, constitutes the critical task, both regarding expitaxy as well as subsequent processing. We address this issue with two profoundly different approaches.

2. 3D All the Way

Processing a resonator on the side facet of a GaN stripe acting as a quasi substrate is disproportionally complicated. Therefore, we decide to create the resonator epitaxially, aside from mirror facets. The GaN stripe not only provides semipolar facets but acts as waveguide with vertical and lateral optical confinement. However, the growth parameters of AlGaN are challenging for selective epitaxy. The high growth temperature promotes lateral growth, subsequently leading to the emergence of an undesirable c-plane facet whereas the reduced selectivity of the mask material for Al atoms leads to polycrystalline growth on masked areas [3, 4]. Furthermore, Wunderer et al. [5, 6] showed that QWs grown on semipolar side facets suffer from a large gradient of the indium content along the facets, explained by gas phase diffusion. This leads to a broad emission spectrum unfavorable for a laser device. In this report, we focus on the former, even more crucial issue.

2.1 Concept - Simulation - Epitaxy

Regrettably, starting with the established growth of GaN stripes and growing the waveguide layer by layer will not suffice. Solving the vectorial Helmholtz equation, the simulation (Fig. 2) shows the rise of multiple modes. In order to provide lateral confinement, the structure has to be adapted to include a high index core of GaN, enclosed by AlGaN claddings. Two possible structures are shown in figures 3 and 4. For concept SM1 (single mode 1) a GaN core with triangular cross-section is positioned on top of a truncated AlGaN stripe and subsequently overgrown with an upper cladding. This concept allows convenient sizes of several micrometers for the mask patterns but demands a delicate

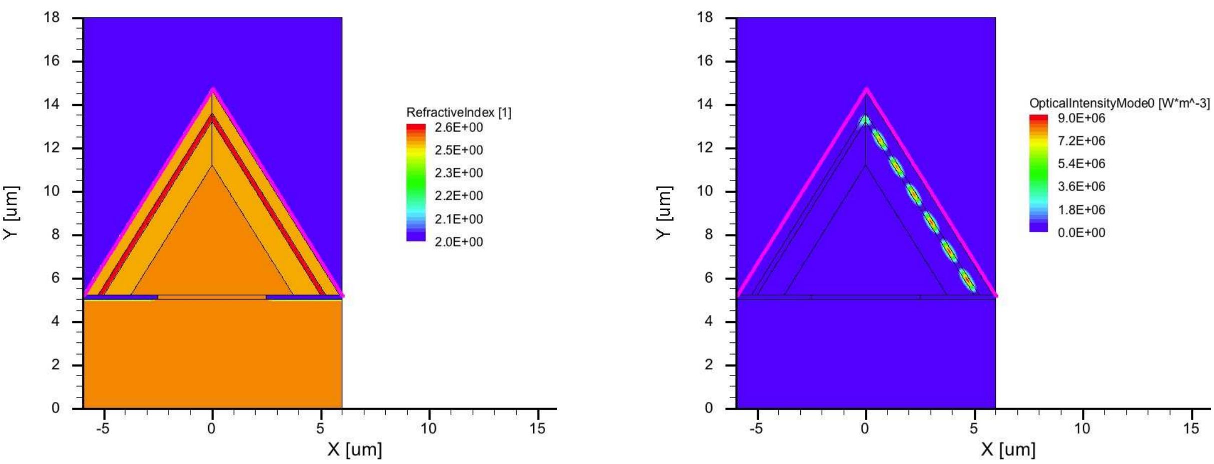

Fig. 2: Concept and simulation of the optical modes for a concept of AlGaN/GaN/AlGaN layers deposited on the side facets of a GaN stripe with triangular cross-section.

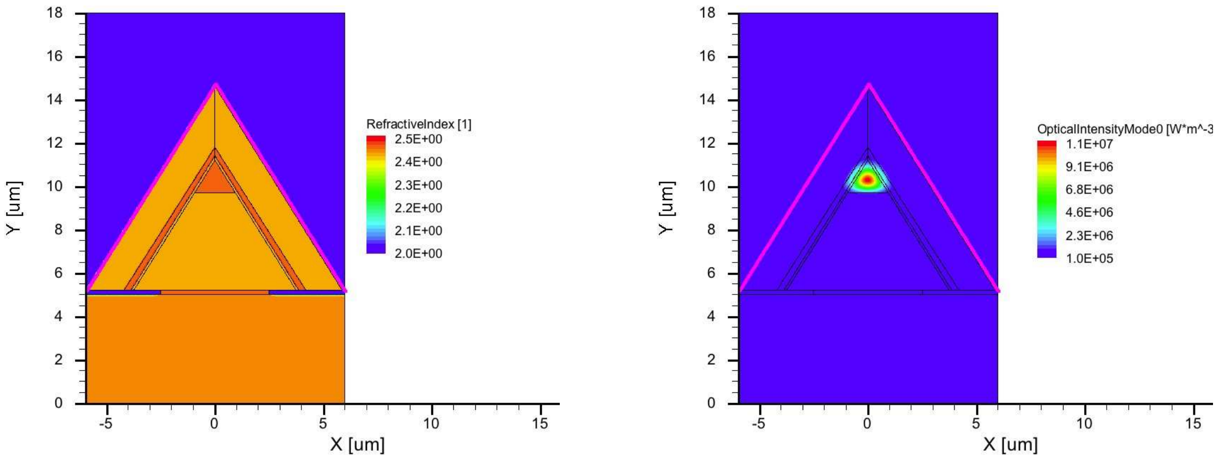

Fig. 3: Concept and simulation of the optical modes for concept SM1. A triangular GaN stripe is grown on top of a truncated AlGaN stripe and consequently enclosed by an upper AlGaN cladding.

control of the epitaxial process in order to obtain a well developed GaN tip before the growth of the second cladding. For concept SM2 the lower AlGaN cladding is realized as a plane layer during the first growth step of the template. After patterning the mask, the GaN core is grown directly at the beginning of the second growth step and subsequently overgrown. The simulation shows good optical confinement for this concept, enhanced by the low refractive index of the dielectric mask ($n = 1.47$ for SiO_2) even for buffer layers with only 5 %, with the advantage of only one 3D growth step of AlGaN needed. Requirements for the mask pattern however are fiercer. In order to get single mode operation the height and base of the GaN core shall not exceed 1.5 µm which is bordering the limits of optical lithography.

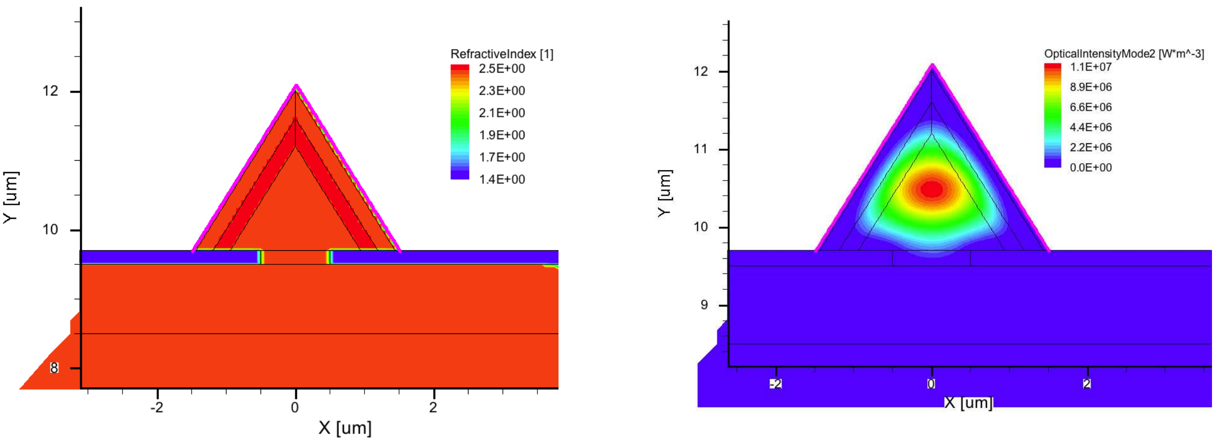

Fig. 4: Concept and Simulation of the optical modes for concept SM2. A planar AlGaN layer is included in the template as the bottom cladding. The waveguide core is directly grown on the template and only one 3D growth step for AlGaN is needed.

2.2 3D growth of AlGaN

For preliminary investigations thin layers, less than 1 µm thick, with low aluminum content (around 5 %) were grown on the side facets of fully developed GaN stripes. On top of an n-doped GaN template, a 200 nm thick SiO_2 mask was deposited by PECVD and patterned by optical lithography and subsequent dry etching. Stripes parallel to $< 10\bar{1}0 >$ or m-direction (resulting in $\{11\bar{2}2\}$ side facets) and stripes parallel to $< 11\bar{2}0 >$ or a-direction (resulting in $\{10\bar{1}1\}$ side facets) with mask opening widths of 4 µm, 6 µm and 8 µm and varying periods were grown. Changing the period and consequently the proportion of masked area results in a local variations of growth conditions. The supply of nitrogen is uniform while the supply of group III elements changes locally with the filling factor leading to local variations of growth rate and V/III ratio, thus giving us a vast parameter set. For this low aluminum content and short growth time, SEM pictures show almost no parasitic nucleation on the mask. With a being the favored growth direction the stripes parallel to a result in stripes with sharp ridges and smooth $\{10\bar{1}1\}$ side facets (not shown) as observed in earlier works [7]. The side is covered with a homogeneous layer of AlGaN, emitting at 351 nm corresponding to approximately 4 % aluminum. The ridge of the stripe exhibits luminescence at higher energy corresponding to approximately 8 % aluminum. This effect seems similar to the indium content gradient in quantum wells on three-dimensional structures. Stripes parallel to m are more prone to lateral growth and exhibit c-plane areas on top as well as rougher sidewalls. Figure 5 shows the cross-section as viewed by SEM as well as spatially resolved low temperature cathodoluminescence (CL). The presence of competing facets aggravates the difference in aluminum content between side facets and tip, nevertheless the $\{11\bar{2}2\}$ facets show a higher aluminum incorporation efficiency than the $\{10\bar{1}1\}$ facets. The CL gives an estimate of approximately 8 % Al content at the top and 5–6 % Al at the sidewalls.

Progressing towards concept SM2, the growth time of the GaN stripe was reduced and the thickness of the covering AlGaN layer was increased. In Fig. 6 the SEM picture of a cross-sections is shown where the material contrast clearly shows the undoped GaN core ensheathed by an AlGaN cladding layer. The exact outlines of the interior cannot be

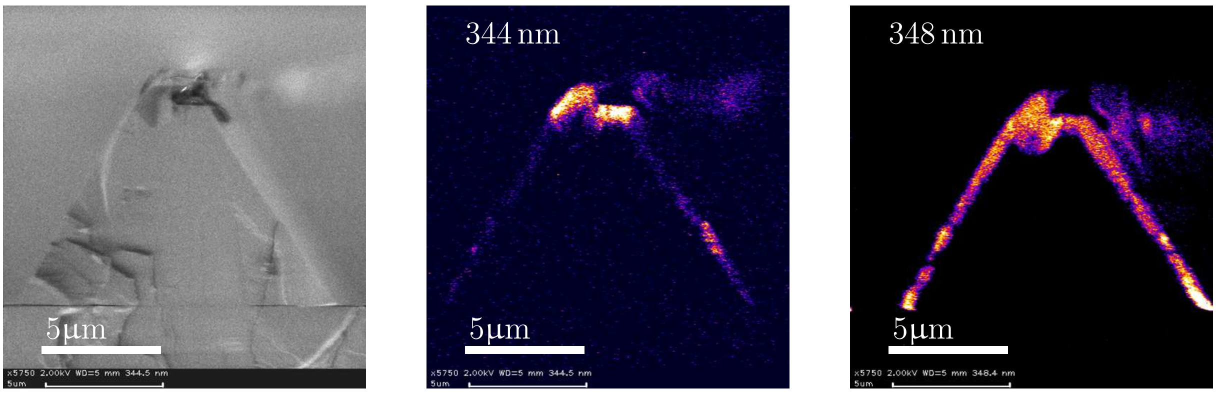

Fig. 5: SEM cross-section and monochromatic CL mappings at 8K of stripe parallel to m with $\{11\bar{2}2\}$ facets. The thin cladding layer of AlGaN is clearly visible. The top of the stripe exhibits luminescence at a higher energy as result of a higher aluminum incorporation.

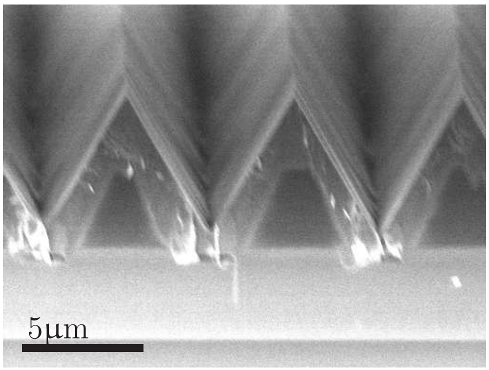

Fig. 6: SEM cross-section of stripes parallel a with $\{10\bar{1}1\}$ facets. The GaN core is overgrown by a thick AlGaN layer.

deduced for certain from this picture, yet the feasibility of the structure SM2 is substantiated. Optimization of the shape, monitored by marker layers and checked by spatially resolved spectroscopy as well as further reduction of the size are necessary. Progressing towards concept SM1, stripes of AlGaN were grown at higher growth temperatures and with more ammonia in order to create a c-plane plateau at the top of the stripe. In the same growth run these plateaus were overgrown with low temperature GaN to create a tip with triangular cross-section, later intended as waveguide core. The upper cladding was not grown. Figure 7 shows a GaN layer on top of the AlGaN plateau, for these dimensions the GaN growth time was not long enough to form a sharp ridge. Clearly visible is the parasitic growth that occurred during the long AlGaN growth and later acts as nucleation site for the low temperature GaN, too. This parasitic growth needs to be suppressed or removed as the mask loses all selectivity once a nucleation has been established. While the growth conditions of AlGaN need to optimized for better mask selectivity to allow the full structure to be realized in one growth run, separating the growth of the SM2 structure into multiple steps can work as a short term workaround. The interruptions will allow removal of parasitic growth by wet etching as well as reestablishing the mask for selective growth.

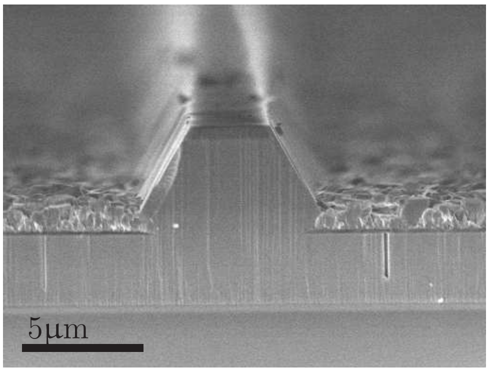

Fig. 7: SEM cross-section of stripes parallel a with $\{10\bar{1}1\}$ side facets. The GaN ridge on top of a truncated AlGaN stripe is clearly visible. Parasitic nucleation on the mask led to polycrystalline growth.

3. Integration by Miniaturization

With an alternate approach we can circumvent almost all difficulties brought about by the three dimensional growth of AlGaN. Decreasing the size of the three-dimensional GaN structures to the point where they fit inside the core of a planar conventional LD design gives the benefits associated with semipolar GaN/InGaN quantum wells without the drawbacks of developing a new waveguide structure. Figure 8 shows the principle idea of this approach. With the mask constituting a perturbation of the refractive index on the scale of the laser wavelength, the device has the potential to work as a DFB laser, additionally.

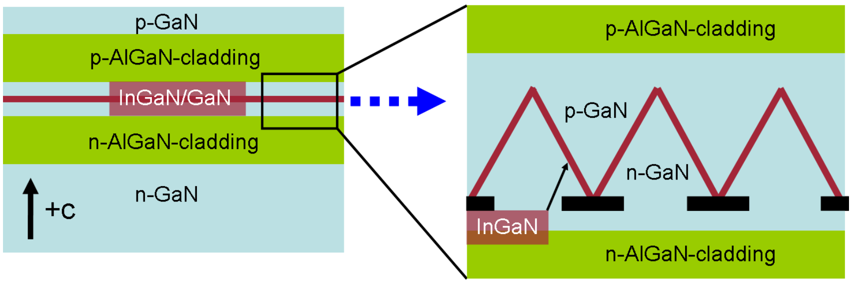

Fig. 8: Shrinking the size of the 3D structures allows the integration of semipolar quantum wells inside a conventional laser diode grown in polar direction.

3.1 Selective growth on a submicrometer scale

In order to reach the submicrometer range of dimensions the dielectric mask needed for selective area growth is reduced to approximately 50 nm thickness and structured via lift-off following e-beam lithography with periodicities of 230 nm to 270 nm corresponding to 3rd order DFB gratings. Our first investigations proved the feasibility of SAG on a submicrometer scale. Figure 9 shows well developed GaN stripes with InGaN/GaN quantum well structures grown on the semipolar side facets. Subsequently these submicrometer structures were planarized with GaN and sandwiched between c-oriented AlGaN waveguide claddings. The planarization and consequently the growth of the upper waveguide cladding depend strongly on the orientation of the stripes. For stripes parallel to a-direction (the favored growth direction) we receive an incomplete embedding whereas for stripes parallel to m-direction the proposed device structure was succesfully realized, shown in Fig. 10.

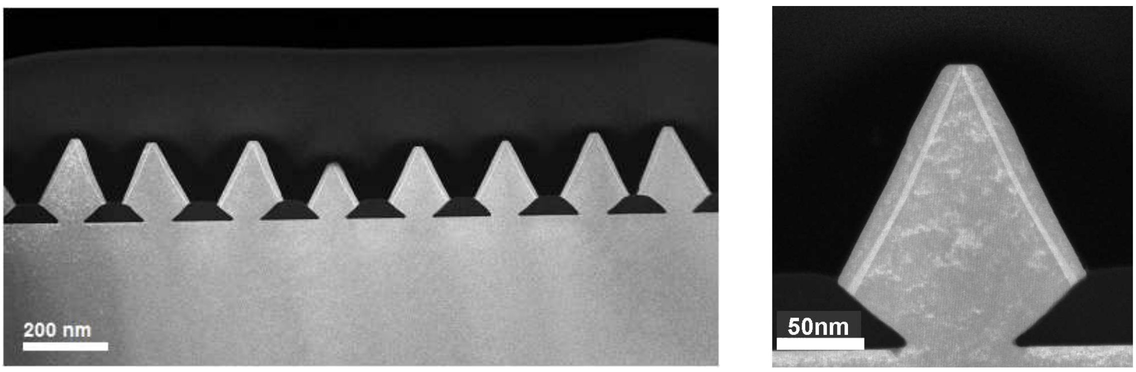

Fig. 9: TEM cross-section images of GaN stripes with semipolar InGaN/GaN quantum wells on the sidefacets.

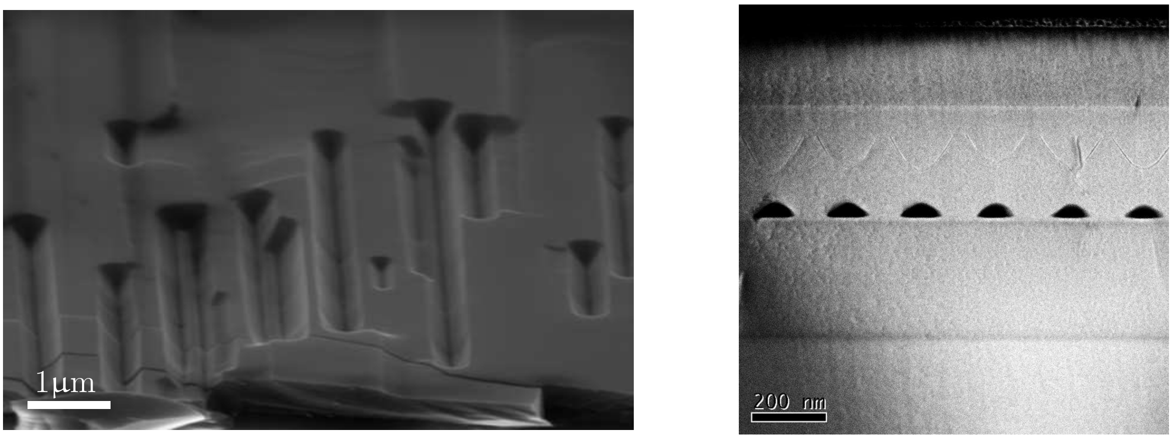

Fig. 10: Comparison of the embedding for different orientations. The SEM picture on the left (topview) shows a sample with stripes oriented along a-directin with $\{10\bar{1}1\}$ facets being incompletely planarized whereas the TEM picture on the right (cross-section) shows the immaculate embedding of a structure with $\{11\bar{2}2\}$ side facets.

3.2 Optical investigation - Gain!

In photoluminescence measurements the strong light matter coupling can be observed by a periodic modulation of the spectra. For the PL spetra in Fig. 11 the sample was excited from the top and the light emitted parallel to the surface plane from cleft edges was collected. We observe a huge difference for light emitted parallel and perpendicular to the stripe orientations owing to the periodic change in refractive index experienced by light emitted perpendicular to the stripes. Obviously, the period of the structure and the wavelength of the QW emission need to be balanced carefully. Nevertheless, figure 12 shows optical gain measurements performed on a first not perfectly planarized test structure. Although the losses and pump power are relatively high, net optical gain was achieved showing great promise for future samples with improved waveguiding.

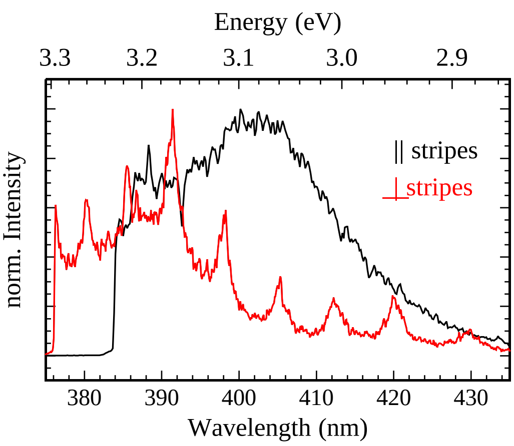

Fig. 11: PL spectra recorded for light emission ∥ and ⊥ to the stripes.

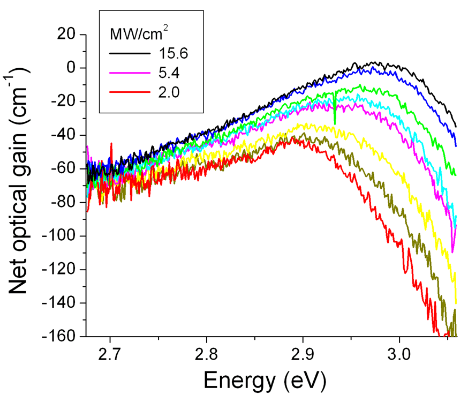

Fig. 12: Optical gain spectra recorded for a not perfectly planarized structure with submicrometer sized 3D GaN structures and semipolar InGaN/GaN QWs.

4. Conclusion

Evolving previously realized designs of light emitting diodes based on selectively grown GaN stripes we have developed two approaches to realize laser diodes with semipolar quantum wells. We have shown the epitaxial feasibility to fabricate an AlGaN/GaN waveguide with triangular cross-section. After establishing a waveguide design, semipolar InGaN/GaN quantum wells are to be included. For the approach of embedding the semipolar quantum wells inside a waveguide grown in polar direction, optical excitation resulted in quantum well emission and optical gain. The focus of further development lies upon improvements of optical confinement and consequent reduction of losses. The simulations were performed at the University of Kassel by B. Witzigmann. Gain measurements were performed by D. Dräger and M. Brendel at the Technical University of Braunschweig. Technical and scientific support by I. Argut, J. Biskupek, R. Blood, A. Chuvilin, F. Demaria, K. Forghani, F. Lipski, Y. Men, S. Schwaiger, W. Schwarz, J. Wang and T. Wunderer is gratefully acknowledged.

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