Sub-μm Patterning for Semipolar GaN Based Light Emitters

Robert A.R. Leute and Dominik Heinz

We present patterning of GaN layers by laser interference lithography to create three-dimensional structures on a submicrometer scale. These structures exhibit surfaces comprised of semipolar crystal facets with reduced piezoelectric fields. The small dimensions of these 3D structures allow embedding. The resulting planarized surfaces considerably ease subsequent device processing. Structural characterization is shown and a first working light emitting device based on embedded submicrometer structures is presented.

1. Introduction

Interest in semipolar GaN crystal planes for efficient green light emitters is not waivering [1]. While the crest is constituted by efforts on free-standing GaN templates for homoepitaxy [2], selective area epitaxy of 3D structures remains suasive [3]. The latter employs relatively cheap 2-inch substrates and growth in c-direction which produces high crystal quality despite heteroepitaxy [4]. For device processing, however, plane surfaces are highly favorable because conventional structuring methods for contacts, resonator formation etc. could be applied. Therefore we seek a method to employ selective area growth for three-dimensional structures with semipolar surfaces only within the active region of our aspired device. The requirement is that the resulting elevation can be planarized easily. Consequently all dimension must be restricted to some hundred nanometers, thus leaving the realms of conventional optical lithography.

2. Subwavelength Lithography: Using Interference Patterns

Laser interference lithography creates periodic patterns with sub wavelength periodicity [5]. The premise is based on the well known Lloyd's mirror interference experiment [6] and given in Fig. 1. The laser beam of a HeCd UV laser ($\lambda = 325\,\mathrm{nm}$) is focused onto a pinhole thereby spread and spatially filtered. Half of the spread beam is directed onto the sample whereas the other half is reflected by a mirror and then directed onto the sample. Thus the two beam halves interfere on the sample surface resulting in a stripe pattern, the periodicity of which depends on the wavelength (λ) of the light source and the angle (2θ) between both incident light beams.

$$P = \frac{\lambda}{2 \cdot \sin\theta} \tag{1}$$

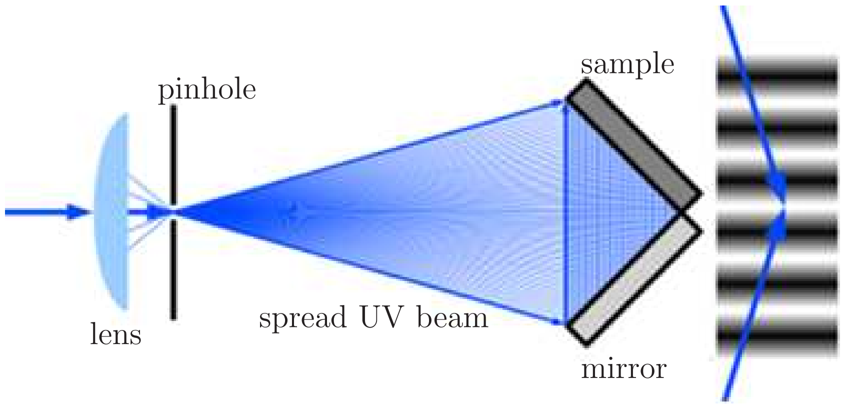


Fig. 1: Schematic drawing of the laser interference lithography setup.

2.1 Submicrometer resist patterns – 1D and 2D

Using a highly sensitive resist AZ MiR 701, diluted with ethyl lactate to get a very thin coating, exposure of a resist layer on GaN with the interference pattern results in a periodic arrangement of stripes, as shown in Fig. 2. We achieved periodicities between 230 nm and 280 nm, the height of the resist stripes is about 80 nm. If exposure time is halved and a second exposure is done with the sample rotated by 90° or 60° the result is a square or hexagonal arrangement of resist colums with 80 nm diameter. These 2D patterns are highly interesting for selective epitaxy of 3D structures like pyramids and inverse pyramids on a sub-µm scale.

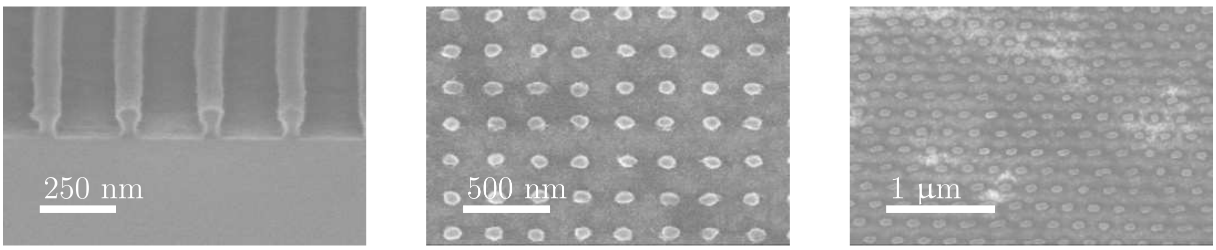


Fig. 2: 1D and 2D resist patterns. The square resist dot arrangement was achieved by a two-time exposure rotated by 90°, the hexagonal arrangement by a two-time exposure with 60° tilt.

3. Selective Epitaxy on a Submicrometer Scale

Pattern transfer to a suitable growth mask for subsequent epitaxy is crucial. A thin layer (15 nm) of titanium is deposited on GaN templates with structured resist. After lift-off the pattern is transfered as an inverted image (see Fig. 3). The templates are then cleaned and transfered into the MOVPE reactor where the Ti mask is nitridized in a hot ammonia atmosphere. Afterwards, the second growth step is carried out. The MOVPE reactor used is an Aixtron-200/4RF-S HT with standard precursors TMGa, TMIn and high purity ammonia. Silane and CP_2Mg are used for doping with Pd diffused hydrogen

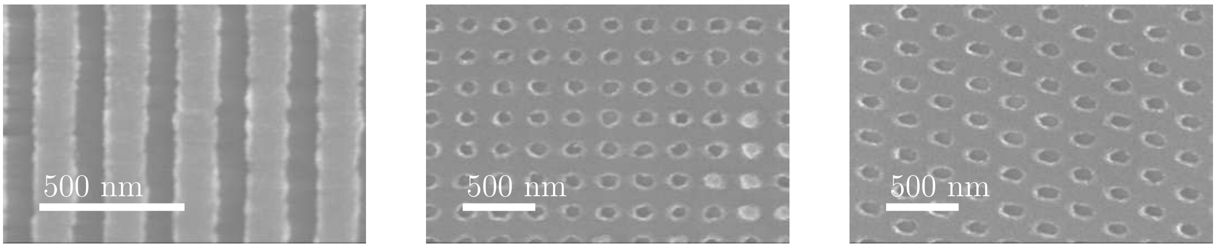


Fig. 3: 1D and 2D mask patterns. 15 nm titanium was evaporated on the resist patterns described above resulting in a negative pattern.

and high purity nitrogen as carrier gases. Growth parameters were chosen based on 3D GaN growth on a supermicrometer scale [7]. For stripes aligned parallel to the a-direction stable growth conditions were obtained, resulting in a homogeneous distribution of stripes over a large area. For 2D patterned masks resulting in nano-pyramids and inverse pyramids the fluctuation of the size distribution observed over the whole wafer was substantial. The overgrowth of 2D patterns seems very sensitive to small deviations of mask and growth parameters. The detailed parameters for all growth modes are given in table 1.

Table 1: Growth parameters for sub-μm sized 3D GaN.

	stripes $\parallel a$	pyramids	inverse pyramids
temperature/°C	970	950	950
pressure/ mbar	150	150	150
V/III ratio	260	310	260
growth time /min	2:00	2:00	3:00

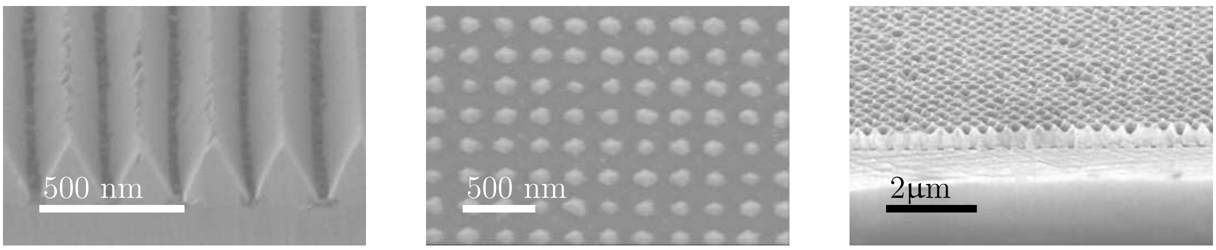


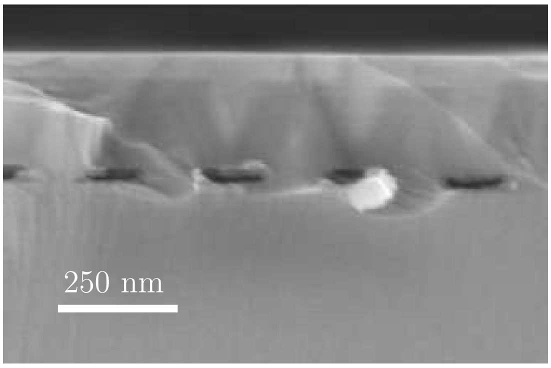
Fig. 4: Depending on mask pattern and growth conditions, several 3D structures can be realized. From left to right: stripes with triangular cross section and $\{10\bar{1}1\}$ side facets, pyramids and inverse pyramids.

4. LED

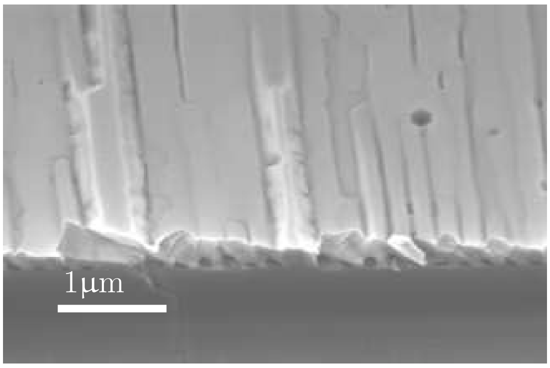
For stripes with triangular cross section aligned parallel to the a-direction with $\{10\bar{1}1\}$ side facets, homogeneous growth over large areas was established, allowing subsequent embedding. In order to facilitate contact evaporation as well as prevent short circuits, a smooth flat surface is required. Based on the samples shown in the previous section, the second growth run is elongated to include a p-doped capping layer.

4.1 Embedding experiments

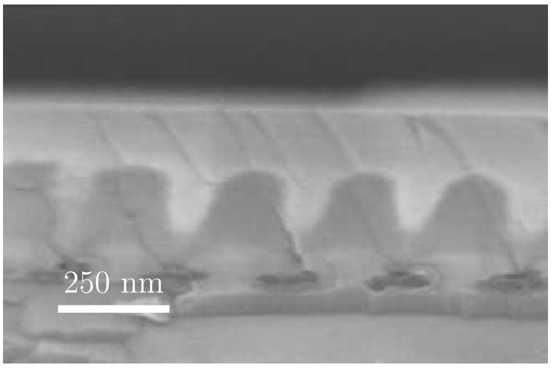
The presence of magnesium is favorable for lateral growth thus facilitating the planarization of the device. However, previous experiments [8] have shown the relative difficulty to planarize stripes with $\{10\bar{1}1\}$ side facets which are very stable. It can be seen in Fig. 5 that sufficient thickness is needed for planarization. Total coverage and a smooth surface was achieved for a growth time equivalent to 250 nm planar growth. Best results were obtained with a high temperature growth step. Further optimization is ongoing.



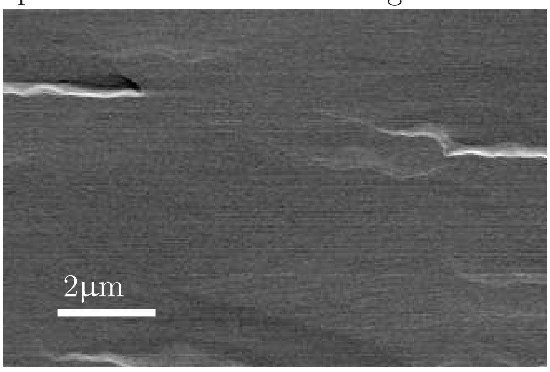
(a): SEM cross section view, non optimized planarization.



(b): SEM bird view, non optimized planarization results in rough surface.



(c): SEM cross section view, the thicker overgrowth leads to a smooth surface.



(d): SEM top view, after thicker overgrowth the surface is smooth with no remnants of the stripes visible.

Fig. 5: Planarization of LED structure before (a), (b) and after (c), (d) optimization.

4.2 Electrical characterization

Circular indium contacts were evaporated on the p-side of the LED. The contacts had diameters ranging vom 70 μm to 140 μm and were 1 μm thick. The n-region was contacted from the top, by creating a trench by mechanical force and filling it with indium. Figure

6 shows voltage and optical output power of the device versus current. The device was stable over a large current range, up to 200 mA. The peak wavelength was 460 nm with a FWHM of 32 nm (spectrum not shown).

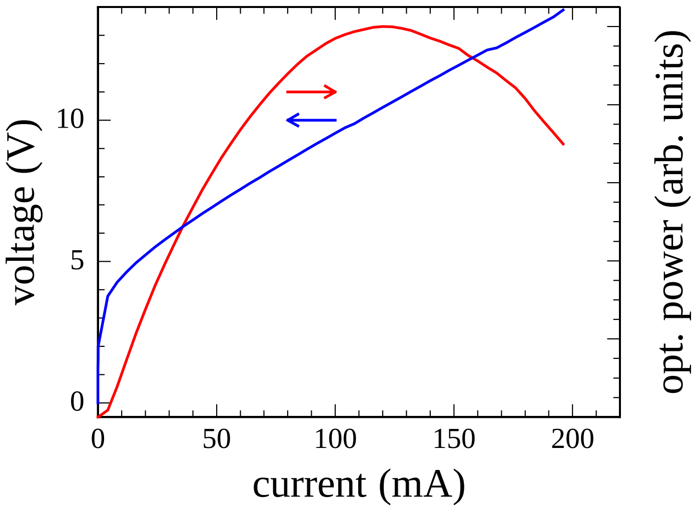


Fig. 6: PIV characteristics obtained for a LED structure via on-wafer testing with circular indium contacts.

5. Conclusion

Laser interference lithography with a Lloyd's mirror geometry was used to pattern GaN on a scale of a few hundred nanometers. The patterned area comprises several cm^2. Employing in-situ nitridized titanium, selective epitaxy of stripes, nanopyramids and inverse pyramids was achieved. Stripes aligned along the GaN a-direction with InGaN quantum wells on the semipolar $\{10\bar{1}1\}$ side facets were embedded and planarized with Mg doped GaN. On wafer testing produced fair electroluminescence stable up to 200 mA.

Acknowledgment

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References

[1] J.S. Speck, "Progress in nonpolar and semipolar GaN materials and devices", *Semiconductor Device Research Symposium (ISDRS), 2011 International 7–9 Dec. 2011*, 2011.

[2] 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.

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

[4] T. Wunderer, M. Feneberg, F. Lipski, J. Wang, R.A.R. Leute, S. Schwaiger, K. Thonke, A. Chuvilin, U. Kaiser, S. Metzner, F. Bertram, J. Christen, G.J. Beirne, M. Jetter, P. Michler, L. Schade, G. Vierheilig, U.T. Schwarz, A.D. Dräger, A. Hangleiter, and F. Scholz, "Three-dimensional GaN for semipolar light emitters", *Phys. Status Solidi B*, vol. 248, pp. 549–560, 2010.

[5] X. Mai, R. Moshrefzadeh, U.J. Gibson, G.I. Stegeman, and C.T. Seaton, "Simple versatile method for fabricating guided-wave gratings", *Appl. Opt.*, vol. 24, pp. 3155–3161, 1985.

[6] Proceedings of the Royal Irish Academy, 1836–1837, Part I, p. 6.

[7] T. Wunderer, *Dreidimensionale Licht emittierende GaInN/GaN-Strukturen mit reduziertem piezoelektrischen Feld*. Ph.D. Thesis, Ulm University, Ulm, Germany, 2010.

[8] R.A.R. Leute, "Laser structures with semipolar quantum wells grown by selective area epitaxy", *Annual Report 2010*, pp. 95–102. Ulm University, Institute of Optoelectronics.