Properties of Semipolar GaInN/GaN Light Emitting Diodes on Selectively Grown GaN Stripes

Thomas Wunderer

Semipolar GaInN/GaN light emitting diodes (LEDs) were investigated as possible candidates for high-brightness devices even in the long wavelength regime. To combine the high material quality known from c-GaN and the advantage of a reduced piezoelectric field, the LED structures were realized on the $\{1\bar{1}01\}$ *side facets of selectively grown GaN stripes that have a triangular shape. Time-resolved and locally resolved photoluminescence (PL) measurements show drastically reduced lifetimes for the semipolar sample of only 650 ps at 4 K whereas we found lifetimes exceeding 50 ns for a polar reference sample. Furthermore, more than a doubling of the PL intensity and a significantly reduced blue shift of the peak wavelength with increasing excitation power provides further evidence for the presence of reduced piezoelectric fields in the semipolar sample. Bright blue light emission with powers as high as* $700\,\mu W$ *and 3 mW could be achieved in electroluminescence measurements under dc conditions for 20 and 110 mA, respectively.*

1. Introduction

GaN-based light emitting devices are still going on to revolutionize general lighting, applications in the automotive industry and data storage. In spite of the high performance achieved up to now, the optical efficiency of current commercially available (Al,Ga,In)N LEDs is limited by negative physical properties caused by the crystal structure and is found to decrease with increasing operational 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 is made possible by rearranging the biaxial strain to planes other than the commonly used [0001] crystal plane (c-plane) [2]. Several groups are currently dealing with this subject by growing heterostructures on the r-plane of sapphire, for instance, in which case GaN grows along the $\langle 11\bar{2}0\rangle$ direction (a-direction) [3, 4]. Other approaches make use of more exotic substrates like $LiAlO_2$ [5], on which pure m-plane GaN $\{1\bar{1}00\}$ growth has been achieved. However, up to now the crystal quality of layers grown on these substrates does not compete with that obtained on the more commonly used c-plane sapphire or SiC wafers, which still limits the optical performance of respective LEDs [6].

These problems may be overcome by starting the epitaxial growth in the *c*-direction, and forming then GaN stripes with less polar side facets by selective epitaxy. QWs and even complete LED structures can then be grown on these facets [7, 8, 9, 10]. Depending on the stripe orientation and growth conditions, different crystal facets can be achieved which possess reduced or even vanishing polarization fields.

2. Fabrication of Semipolar GaInN/GaN Stripe LEDs

The samples were grown by low pressure metalorganic vapor phase epitaxy (MOVPE). First, 1.6 μm thick GaN templates were grown on *c*-plane sapphire. These were subsequently structured using SiO_2 stripes oriented along the $\langle 11\bar{2}0\rangle$ direction, fabricated by plasma enhanced chemical vapor deposition (PECVD), optical lithography and reactive ion etching (RIE). The parameters of the second epitaxial step have been tailored to grow triangularly shaped *n*-doped GaN stripes in the several μm wide mask openings which have $\{1\bar{1}01\}$ side facets as the most stable surface. Thereafter, five GaInN quantum wells were grown covered by a GaN:Mg layer (Fig. 1). Circular mesa structures with diameters between 70 and 140 μm were realized by chemically assisted ion beam etching (CAIBE). For simple and highly reflective contacts, electron beam deposited indium (1 μm) was used for the *p*-GaN as well as for the *n*-GaN metallization without alloying.

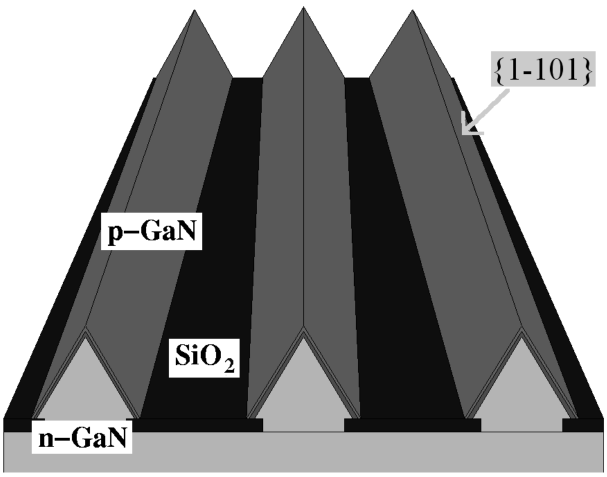

Fig. 1: Schematic sketch of the semipolar LED structure.

3. Mg-doped GaN: Problems and Solutions

An important aspect, which requires careful optimization, is the growth of the *p*-type regions. Depending on the magnesium fraction we found a very strong anisotropic growth behavior for the Mg-doped top layer. Preferential lateral growth appears when using growth parameters known from *c*-plane epitaxy. This results in an extremely thin cover layer at the apex of the stripes. Without Mg doping, we found preferential growth along the *c*-direction on the top areas.

Since Mg is needed for the *p*-type doping of GaN and due to the fact that the growth rate at the partially flat top is lower than on the side facets, there is a risk for electrical shorts at the top when the metallization is in direct contact with the *n*-GaN or the QWs. Indeed, we observed high leakage currents of more than 5 mA @ -2 V for such devices. Therefore we developped, on the one hand, an additional process to achieve an electrically isolating Al_2O_3 coating on the apex of the stripe. This was done by spinning a thin fluid photo resist onto the sample. The resist covers the apex only with a thin film, in contrast to the gap between the stripes where it is relatively thick. Thereon the apex is freed from the resist in an O_2 plasma asher und coated by sputtering Al_2O_3 under a tilted position. After a lift-off process the isolating coating remains only on the apex. On the other hand, we optimized our epitaxial growth process in order to get an appropriate magnesium fraction into the top layer in combination with a closed apex. Therefore, we developed a more-step process with different Mg-concentrations to achieve a fully closed GaN:Mg top layer. Of course, this in-situ step is the favored procedure (see Fig. 2).

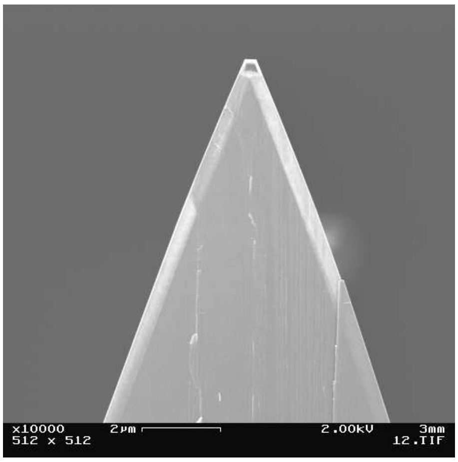

Fig. 2: More-step growth with different Mg-concentrations to achieve fully closed GaN:Mg top layer.

4. Luminescence Properties

To investigate the luminescence properties of the semipolar sample time-resolved photoluminescence and time-integrated electroluminescence measurements were performed. A *c*-plane reference sample with the same structural and compositional properties was used in order to allow for a reliable comparison.

4.1 Time-resolved photoluminescence

The micro-PL investigations were performed in a helium-flow cryostat at a temperature of 4 K. The laser excitation was realized by frequency doubling (350-500 nm) the output of a tunable Ti:Sapphire laser system which provides 120 fs pulses with a pulse repetition time of 13.1 ns. An excitation wavelength of 380 nm was chosen in order to quasi-resonantly excite the GaInN QW layers. The laser emission could be focused down to a diameter of approximately 1 µm using a long-working-distance 50x microscope objective mounted on a piezo-based actuator which is capable of a spatial resolution of 50 nm. The sample region of interest could be accurately selected as the cryostat can be moved both horizontally and vertically using two orthogonally mounted stepper motors each with an effective spatial resolution of 50 nm. In the case of the semipolar stripe sample a special holder with a 60° sample mounting plane was used in order to match the triangularly shaped semipolar stripe edge facet angle and to thereby achieve sample excitation and PL collection normal to the stripe edge surface. The PL was dispersed using a 0.75 m spectrometer and detected using either a liquid-nitrogen-cooled charge-coupled-device camera when recording time-integrated spectra, or a fast avalanche photodiode with a time resolution of 40 ps when performing time-resolved photoluminescence (TRPL) via the time correlated single photon counting technique.

Theoretical calculations have predicted a reduced piezoelectric field on the $\{1\bar{1}01\}$ side facets of selectively grown GaN stripes [2, 11, 12]. Thus, the local separation of electrons and holes in the strained GaInN/GaN QWs should be reduced with respect to conventional c-plane LEDs and consequently an enhanced recombination probability should be found. Hence, besides a reduced carrier lifetime an increased luminescence intensity is expected for the semipolar stripe LEDs.

Actually, both aspects could be verified. Fig. 3 a) shows the TRPL intensity of the semipolar sample at an excitation power of 200 µW, a power which corresponds to a power density of approximately 25 kW/cm^2. At this excitation power density at the peak wavelength of 432 nm, the decay time was determined to be 650 ps at 4 K.

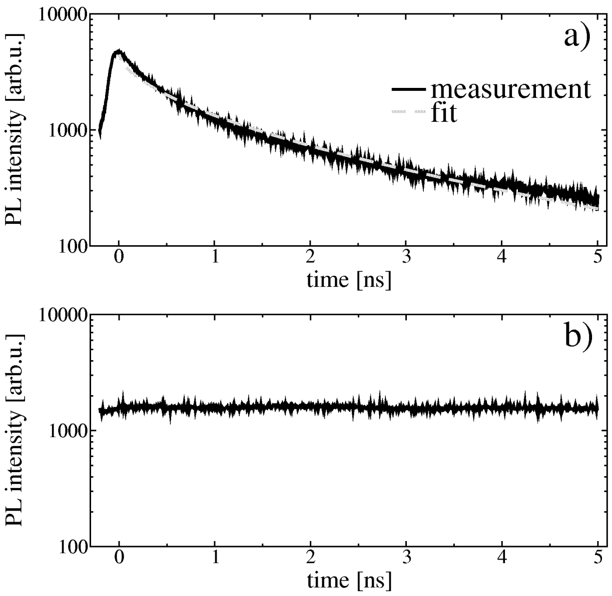

Fig. 3: a) PL decay of the semipolar LED measured at the peak wavelength and an excitation power of 200 µW at 4 K. The decay time is determined to be 650 ps.
b) PL decay of the polar LED measured at the peak wavelength and an excitation power of 200 µW at 4 K. The PL decay time in this case is > 50 ns.

The values were determined by fitting the measured data using the equation

$$I(t) = I_0 \exp\left[-\left(\frac{\mathrm{t}}{\tau}\right)^{\beta}\right], \quad (1)$$

where $I(t)$ is the PL intensity as a function of time and β can vary between 0 and 1. The PL kinetics can be well described by this stretched exponential, which is typically used to describe disordered systems. Nanoscale fluctuations of the indium concentration can produce forms of disordering that are responsible for the non-monoexponential decay observed from GaInN-LEDs [13].

In contrast, very long decay times of more than 50 ns [14] are observed on the *c*-plane reference sample (Fig. 3 b)). Such data are not unusual for high quality, relatively thick GaInN/GaN QWs emitting within this wavelength range [15, 16] and emphasize the fact that the presence of a high piezoelectric field increases the radiative lifetime.

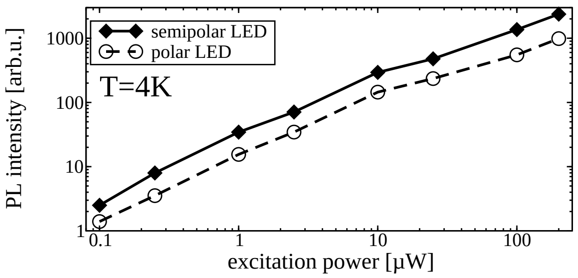

Fig. 4: Integrated PL intensity of the semipolar and polar LED structures measured at 4 K. The emission wavelength can be extracted from Fig. 5.

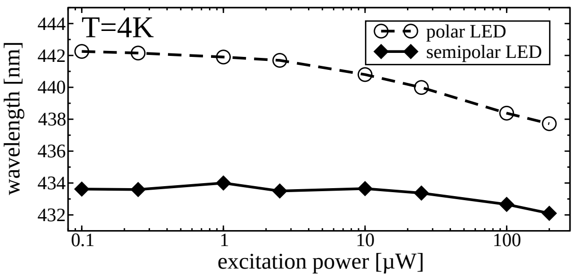

Fig. 5: PL peak shift due to screening of the built-in electric fields for both the semipolar and polar LEDs.

Analyzing the integrated PL intensity of both LED structures (Fig. 4), we found more than twice the optical output power of the semipolar sample than that of the polar sample across the investigated excitation range from 100 nW to 200 μW. This is in good agreement with that predicted by theoretical calculations [11, 12]. This significant improvement is primarily believed to originate from the reduced piezoelectric field.

Free photoexcited carriers in the QWs are expected to lower the influence of the QCSE by screening. This can also give rise to a decrease in PL decay time and to a blueshift of the peak emission wavelength with increasing excitation power.

Indeed, no significant change of the decay time with increasing excitation power could be observed for the semipolar LED. Also, the PL peak position of the semipolar sample shows a much weaker shift with excitation power as compared to the reference (Fig. 5) which emphasizes the proposition that the piezoelectric field is reduced on the $\{1\bar{1}01\}$ side facets of the GaN stripes.

4.2 Time-integrated electroluminescence

The electroluminescence characteristics of the diodes were quantified by on-wafer probing of the devices. The measurement of the optical output power was performed with an integrating sphere and a calibrated Si photo diode. For the electroluminescence spectra light was coupled into a glass fiber and analysed with an Ando AQ-6315A optical spectrum analyser. All measurements were carried out at room temperature.

Semipolar LEDs with a completely closed GaN:Mg top layer show low leakage currents in the range of 200-300 pA @ -2 V. As indium is used for the *p*- and *n*-contacts, the *I*-*V* characteristic is not optimized for operation in forward direction yet. A more sophisticated metallization, e.g. Ni/Au in combination with a highly reflective layer and Ti/Al/Ni/Au for the *p*- and *n*-contact, respectively, should lead to a further improvement of the electrical properties.

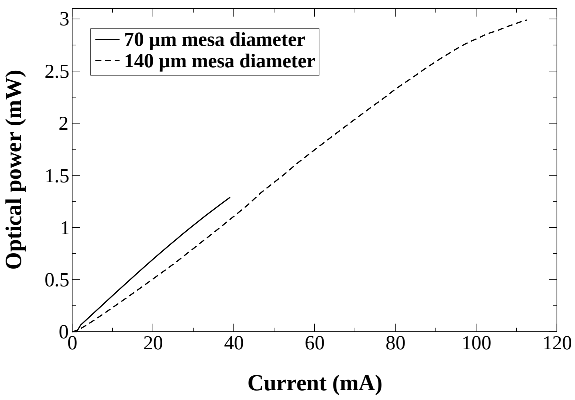

Fig. 6: Optical output power of semipolar facet LED with circular shaped mesa with 70 and 140 µm diameter.

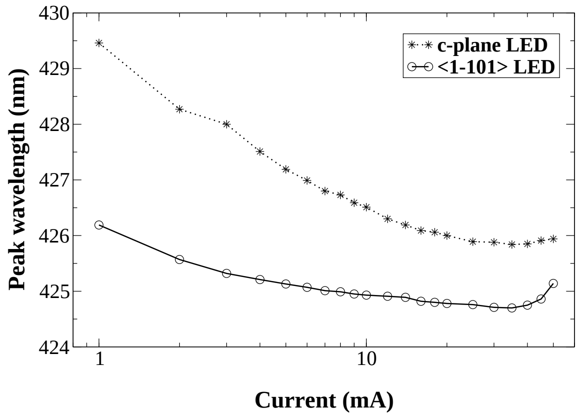

Fig. 7: Shift of EL wavelength caused by screening effects of the electrical field; comparison between polar and semipolar facet LED for currents between 1 and 50 mA.

In Fig. 6 the optical output power under dc operation is shown for devices with mesa diameters of 70 and 140 µm. Bright electroluminescence of 700 µW @ 20 mA and up to 3 mW @ 110 mA at a wavelength of 425 nm could be achieved on-wafer under dc conditions confirming the good performance of our LEDs.

On increasing injection current, a blue shift of the effective emission wavelength is expected due to screening effects of the electrical field. According to this, the shift for our LEDs should be smaller than that known from *c*-plane LEDs because of a reduced piezoelectric field. Actually, this could be verified (fig. 7). The wavelength shift for dc currents ranging from 1 to 50 mA was 1.5 nm for our semipolar LEDs in comparison to 3.5 nm for our reference polar *c*-plane LEDs. Similar to the much weaker wavelength shift in photoluminescence, this value fits well to theoretical data, where a field reduction by a factor of 2.8 is predicted for our semipolar facets [2].

5. Conclusion

In summary, we have reported on the properties of semipolar blue GaInN/GaN MQW LEDs realized on the $\{1\bar{1}01\}$ side facets of selectively grown GaN stripes running along $\langle 11\bar{2}0 \rangle$. Time-resolved photoluminescence measurements showed relatively short decay times of 650 ps at an excitation power of 200 µW at 4 K for the semipolar sample while decay times > 50 ns were determined for the polar *c*-plane LED. Furthermore, the integrated PL intensity of the semipolar sample is observed to be more than twice that of the polar reference sample over the three orders of magnitude power range. CW on-wafer optical output powers as high as 700 µW and 3 mW were measured in electroluminescence for drive currents of 20 mA and 110 mA, respectively. A reduced wavelength shift due to screening effects could be observed in both luminescence experiments and confirms the reduced piezoelectric field in our LED structures.

Acknowledgment

We would gratefully acknowledge the cooperation with Gareth J. Beirne, Michael Jetter and Peter Michler from the Institut für Strahlenphysik at the University of Stuttgart and Martin Feneberg and Klaus Thonke from the Institute of Semiconductor Physics at the Ulm University.

References

[1] J. Edmond, A. Abare, M. Bergman, J. Bharathan, K.L. Bunker, D. Emerson, K. Haberern, J. Ibbetson, M. Leung, P. Russel, D. Slater, "High efficiency GaN-based LEDs and lasers on SiC", *J. Cryst. Growth*, vol. 272, pp. 242–250, 2004.

[2] T. Takeuchi, H. Amano, I. Akasaki, "Theoretical Study of Orientation Dependence of Piezoelectric Effects in Wurtzite Strained GaInN/GaN Heterostructures and Quantum Wells", *Jpn. J. Appl. Phys.*, vol. 39, pp. 413–416, 2000.

[3] H. Ng, "Molecular-beam epitaxy of GaN/$Al_xGa_{1-x}N$ multiple quantum wells on *R*-plane $(10\bar{1}2)$ sapphire substrates", *Appl. Phys. Lett.*, vol. 80, pp. 4369–4371, 2002.

[4] M. Craven, P. Waltereit, F. Wu, J. Speck, S. DenBaars, "Characterization of *a*-Plane GaN/(Al,Ga)N Multiple Quantum Wells Grown via Metalorganic Chemical Vapor Deposition", *Jpn. J. Appl. Phys.*, vol. 42, pp. L235–L238, 2003.

[5] P. Waltereit, O. Brandt, A. Trampert, H. Grahn, J. Menniger, M. Ramsteiner, M. Reiche, K. Ploog, "Nitride semiconductors free of electrostatic fields for efficient white light-emitting diodes", *Nature*, vol. 406, pp. 865–868, 2000.

[6] A. Chakraborty, B. Haskell, H. Masui, S. Keller, J. Speck, S. DenBaars, S. Nakamura, U. Mishra, "Nonpolar *m*-Plane Blue-Light-Emitting Diode Lamps with Output Power of 23.5 mW under Pulsed Operation", *Jpn. J. Appl. Phys.*, vol. 45, pp. 739–741, 2006.

[7] T. Takeuchi, S. Lester, D. Basile, G. Girolami, R. Twist, F. Mertz, M. Wong, R. Schneider, H Amano, I. Akasaki, "Polarization Control in Nitride-Based Semiconductor", *IPAP Conf. Series*, vol. 1, pp. 137–140, 2000, Proc. Int. Workshop on Nitride Semiconductors.

[8] K. Nishizuka, M. Funato, Y. Kawakami, S. Fujita, Y. Narukawa, T. Mukai, "Efficient radiative recombination from $\langle 11\bar{2}2\rangle$-oriented $In_xGa_{1-x}N$ multiple quantum wells fabricated by the regrowth technique", *Appl. Phys. Lett.*, vol. 85, pp. 3122–3124, 2004.

[9] S. Khatsevich, D.H. Rich, X. Zhang, W. Zhou, P.D. Dapkus, "Temperature dependence of excitonic recombination in lateral epitaxially overgrown InGaN/GaN quantum wells studied with cathodoluminescence", *J. Appl. Phys.*, vol. 95, pp. 1832–1842, 2004.

[10] T. Wunderer, P. Brückner, B. Neubert, F. Scholz, M. Feneberg, F. Lipski, M. Schirra, K. Thonke, "Bright semipolar GaInN/GaN blue light emitting diode on side facets of selectively grown GaN stripes", *Appl. Phys. Lett.*, vol. 89, pp. 041121–041123, 2006.

[11] A.E. Romanov, T.J. Baker, S. Nakamura, J.S. Speck, "Strain-induced polarization in wurtzite III-nitride semipolar layers", *J. Appl. Phys.*, vol. 100, pp. 023522–023532, 2006.

[12] M. Feneberg, F. Lipski, R. Sauer, K. Thonke, T. Wunderer, B. Neubert, P. Brückner, F. Scholz, "Piezoelectric fields in GaInN/GaN quantum wells on different crystal facets", *Appl. Phys. Lett.*, vol. 89, pp. 242112–242115, 2006.

[13] M. Pophristic, F.H. Long, C. Tran, I.T. Ferguson, R.F. Karlicek, Jr., "Time-resolved photoluminescence measurements of InGaN light-emitting diodes", *Appl. Phys. Lett.*, vol. 73, pp. 3550–3553, 1998.

[14] In our measurement setup, the time between succeeding laser pulses is 13 ns. The decay time is therefore only estimated to be > 50 ns.

[15] F. Scholz, "Metalorganic vapor phase epitaxy of GaN and GaInN/GaN heterostructures and quantum wells", *Prog. Cryst. Growth and Charact.*, vol. 35, pp. 243–262, 1997.

[16] H. Gotoh, T. Tawara, Y. Kobayashi, N. Kobayashi, T. Saitoh, "Piezoelectric effects on photoluminescence properties in 10-nm-thick InGaN quantum wells", *Appl. Phys. Lett.*, vol. 83, pp. 4791–4793, 2003.