Efficiency Studies of Semipolar GaInN-GaN Quantum Well Structures

Tobias Meisch and Ferdinand Scholz

In order to clarify the reasons for the fairly poor electroluminescence (EL) performance of semipolar LED structures grown on patterned sapphire wafers, we have analyzed both, pure photoluminescence (PL) test structures without doping only containing 5 GaInN quantum wells and full EL test structures, all emitting at a wavelength of about 510 nm. Evaluating the PL intensity over a wide range of temperatures and excitation powers, we conclude that such quantum wells possess a fairly large internal quantum efficiency of about 20 %. However, on EL test structures containing nominally the same quantum wells, we obtained an optical output power of only about 150 µW at an applied current of 20 mA. This may be due partly to some thermal destruction of the quantum wells by the overgrowth with p-GaN. Even more important seems to be the not yet finally optimized p-doping of such structures.

1. Introduction

As discussed in our previous annual report contributions (see, e.g., [1]) and in other publications (see, e.g., [2] and references therein), the efficiency of green light emitting diodes based on GaN heterostructures is still significantly inferior as compared to their blue light emitting counterparts. Such longer wavelength emission requires an increased In content in the active quantum wells of these devices leading — on the one hand — to a more defective material owing to the increasing lattice mismatch to the GaN host material and the need to use fairly low growth temperatures for such In-rich layers. On the other hand, these quantum wells are heavily pseudomorphically strained causing strong internal piezoelectric fields leading to a tilt of the valence and conduction band in the quantum wells. Consequently, the wave functions of electrons and holes get spatially separated and the recombination probability is predicted to be significantly reduced [3]. These piezoelectric fields can be reduced or even avoided by growing such heterostructures in non-c-directions. While nonpolar GaN structures typically possess a poor crystal quality, semipolar growth directions like $\{11\overline{2}2\}$, $\{10\overline{1}1\}$, or $\{20\overline{2}1\}$ are a promising compromise between a reasonable crystal quality and a reduced internal field.

Our investigations focus on the growth of semipolar $\{11\overline{2}2\}$ GaN heterostructures on $\{10\overline{1}2\}$ trench-patterned sapphire substrates, similar as reported by Okada et al. [4]. The GaN, nucleating on the inclined c-side-facets of these trenches, first grows in the well-established c-direction, then forms triangularly shaped stripes and eventually coalesces after a suitable growth time to a planar $\{11\overline{2}2\}$ oriented surface [2, 5]. On such planar semipolar surfaces, the growth of semipolar GaInN quantum wells and complete LED or laser diode structures in a single epitaxial run is possible. The wafer diameter is just limited by the reactor size. In our studies, 2" diameter sapphire wafers were used.

The main goal of these studies was the evaluation of the quantum efficiency of our semipolar quantum wells for emission wavelengths beyond 500 nm. As reported earlier [1,6], our semipolar LEDs emit comparably weak light intensities of about 100 µW at 20 mA. The current studies should help to clarify whether this is mainly caused by the limited quantum well quality or whether the p- and n-type doping of the outer barrier layers may be responsible for this behavior. Therefore, we have investigated the characteristics of GaInN quantum wells grown on previously optimized [5] semipolar GaN templates and of complete LED test structures. This required further optimisation of the p-doped layers which will also be discussed here. Magnesium, the only acceptor applicable to GaN, needs to be incorporated in huge concentrations, typically in the range of several $10^{19}\,\mathrm{cm}^{-3}$ for hole concentrations still below $10^{18}\,\mathrm{cm}^{-3}$ [7] owing to its large activation energy of about 180 meV [8]. Even worse, the Mg incorporation in $\{11\overline{2}2\}$-oriented GaN is reported to be less efficient than on c-plane surfaces [9–11]. Somewhat higher concentrations have been obtained for lower growth temperatures, helping to overcome the quite large parasitic n-type background [1]. However, only a small Mg concentration window seems to be suitable for good semipolar LED performance.

2. Experimental

As reported earlier in more detail [1], trenches have been defined by optical lithography and then etched into $(10\overline{1}2)$ oriented sapphire wafers by reactive ion etching leading to *c*-plane-like facets on one side of the stripes. All other facets have been covered by directional sputtering of SiO_2 in order to prevent parasitic growth.

The MOVPE growth was done in a commercial Aixtron-200/4 RF-S HT reactor using the standard precursors ammonia (NH_3), trimethylgallium (TMGa), trimethylaluminum (TMAl) and trimethylindium (TMI). For doping, silane (SiH_4) and bis(cyclopentadienyl)-magnesium (Cp_2Mg) have been used. The details of the nominally undoped GaN buffer layer growth including a defect-reducing SiN interlayer up to a total thickness of about 5 µm is described in [1]. On top of such templates, GaInN-GaN quantum well test structures with 5 quantum wells have been grown with a quantum well width L_z of about 2.2 nm and a GaN barrier width L_B of about 6.5 nm. In order to achieve an emission wavelength beyond 500 nm, we have chosen quite low growth temperatures of 725 °C and 760 °C for wells and barriers, respectively. The top GaN layer was grown at the same conditions as the GaN barriers with a thickness of about 13 nm in order to allow efficient photoluminescence excitation even with a HeCd laser. For LED test structures, a 2 µm thick Si-doped GaN layer was grown between buffer and first quantum well with a nominal Si concentration of about $10^{19}\,\mathrm{cm}^{-3}$. After the last quantum well, 30 nm of undoped GaN have been deposited to minimize back-diffusion of Mg into the quantum wells. The structure was finalized by a Mg-doped p-GaN layer with a thickness of 100 nm. This layer was grown at a temperature of 910 °C, where we observed a larger Mg incorporation as compared to higher temperatures [1]. Moreover, such fairly low capping layer temperature minimizes the detrimental thermal load to the GaInN quantum wells. More details of the Mg doping of this layer will be discussed later in this report. In order to have a low contact resistivity, an even higher doped cap layer with a thickness of about 10 nm was grown on top.

The quantum well structures were evaluated by photoluminescence (PL) at various excitation powers by mainly using a GaN-based laser diode with a wavelength of 405 nm and a maximum output power of more than 300 mW as excitation source. Simple p-type contacts with a diameter of 90 µm have been processed on the LED test structures by evaporating In, whereas the n-type contact has been formed by scratching the surface down to the n-GaN layer. The optical output power of these structures was measured on-wafer under DC conditions inside an integrating sphere at room temperature without additional light outcoupling features.

3. Photoluminescence of Semipolar Quantum Wells

In order to find out, whether the semipolar quantum wells are significantly inferior as compared to common polar ones, we have investigated our structures by PL in a wide temperature range between 10 K and room temperature. Thus, we can estimate the internal quantum efficiency as the PL intensity ratio between room temperature and low temperature, if we assume a pure radiative emission at low temperature.

Our QW samples show indeed a quite strong PL at low temperature and at room temperature (Fig. 1).

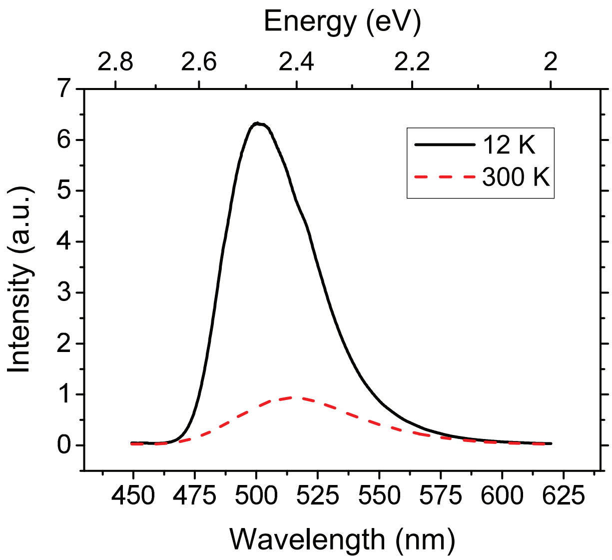

Fig. 1: PL spectra of one of our quantum well structures at low and room temperature.

The PL intensity of such quantum well structures is expected to be governed by the well-known *ABC-model*. The total spontaneous recombination rate R_{total} is given by

$$R_{\text{total}} = A \cdot n + B \cdot n^2 + C \cdot n^3 \tag{1}$$

where n describes the carrier concentration, A is the coefficient describing non-radiative transitions according to the Shockley-Read-Hall model, B represents the radiative recombination coefficient, and C is the Auger coefficient. Hence the radiative efficiency, also called "internal quantum efficiency" η_{IQE} depends on the carrier concentration according to

$$\eta_{\mathrm{IQE}} = \frac{R_{\mathrm{rad}}}{R_{\mathrm{total}}} = \frac{B \cdot n^2}{A \cdot n + B \cdot n^2 + C \cdot n^3}. \tag{2}$$

Consequently, the internal quantum efficiency η_{IQE} is expected to change with carrier concentration. In order to get reliable data, we therefore have measured the PL intensity as a function of excitation intensity at many temperatures (Fig. 2).

Indeed, we found that the intensity ratio between room temperature and low temperature at a given laser excitation power is fairly constant in this range of excitation power. This ratio is often interpreted as internal quantum efficiency, assuming that the non-radiative coefficient A is negligible at low temperature and hence the recombination rate at low temperature is purely radiative. This assumption is fair if this ratio saturates at a high level for temperatures close to 0 K (Fig. 3). On the other hand, the Auger term should be still negligible, i.e. the excitation power should be not too large, being visible by the fact, that the PL efficiency does not yet decrease with increasing excitation power (Fig. 2). Hence, these data (Fig. 3) allow us to estimate a fairly large internal quantum efficiency of $\eta_{\mathrm{IQE}} > 25\,\%$, which is confirmed by a comparably strong absolute PL intensity of these semipolar QWs.

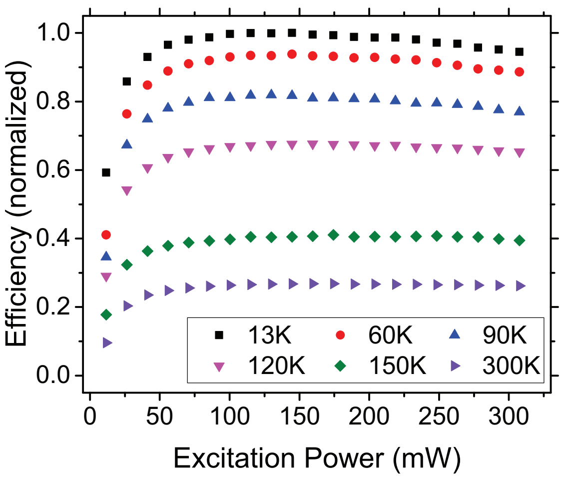

Fig. 2: Ratio of integrated photoluminescence intensity and excitation power (normalized) versus excitation laser power measured at various temperatures.

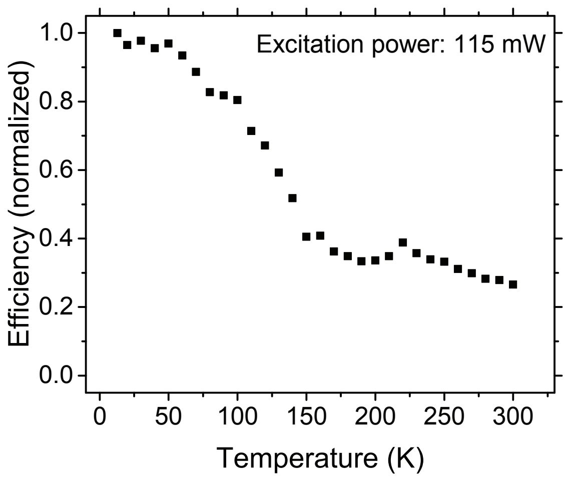

Fig. 3: Ratio of integrated photoluminescence intensity and excitation power (normalized) versus temperature at a laser excitation power of 115 mW.

As expected, our semipolar quantum wells show only a minor wavelength shift with excitation power between 10 and 300 mW of about 3 nm (Fig. 4, left), while a similarly grown polar quantum well structure shifts by 13 nm (Fig. 4, right), although emitting at somewhat shorter wavelength. Such a shift is a consequence of a screening of the internal

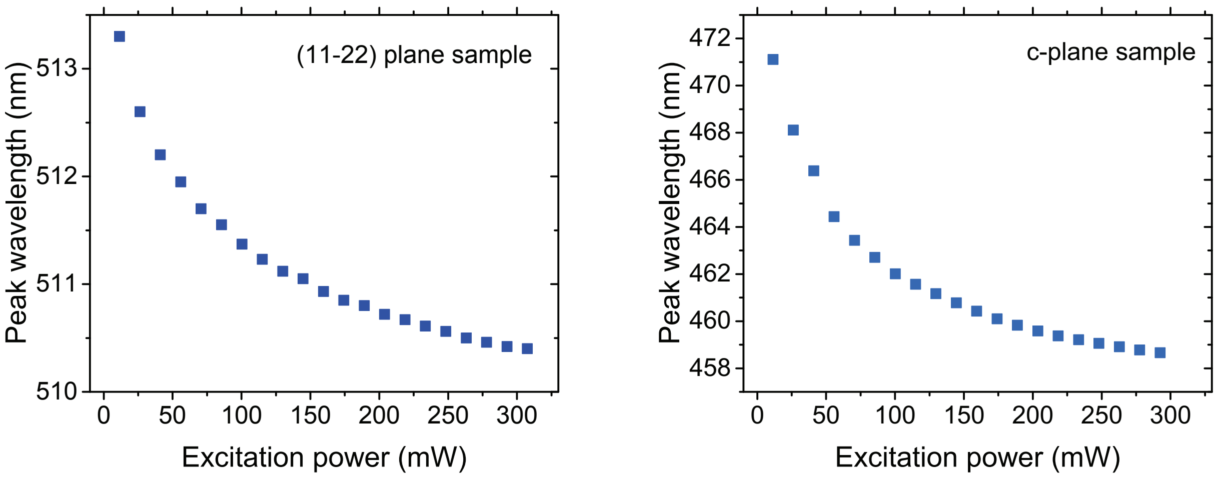

Fig. 4: PL peak shift of a semipolar QW structure (left) and a similar polar structure (right) at room temperature for the same excitation power range.

piezo-electric field in the quantum wells by the excited carriers. Hence, a smaller shift confirms the smaller electric field in our semipolar quantum wells.

4. Electroluminescence from Semipolar Test Structures

As described above, we have embedded such QWs into n- and p-doped GaN layers thus forming an electroluminescence test structure, which can be regarded as a simple semipolar light emitting diode (LED). As discussed previously, the Mg doping was carefully optimized. This eventually resulted in p-doped semipolar GaN layers despite the still fairly large n-type background as directly proven by Hall experiments [1]. Indeed, p-type behavior could be only obtained in a small window of Mg fluxes (Fig. 5). At low Mg flux, the n-background dominates, whereas at large flux, we assume that self-compensation effects lead again to n-type behavior as well-known for polar structures [7].

Accordingly, the LED performance seems to be very sensitive to the Mg flow during the growth of the top p-GaN layer (Fig. 6).

For the best Mg flow the total light output power reaches 150 µW at a current of 20 mA. Although being quite large as compared to other results obtained for semipolar LEDs on foreign substrates (see, e.g., [12]), this value still represents a wall-plug efficiency of $\eta_{\mathrm{WPE}} < 0.25\,\%$. Even if we assume fairly large losses by a low light extraction efficiency, such values seem to indicate that the internal quantum efficiency of our LED structures is much lower than those 20 % or so which we measured on our PL structures (see Sect. 3). In order to check whether the QWs of our LEDs are indeed worse than those of our PL structures, we have measured the PL intensities of both types of structures side by side carefully establishing similar measurement conditions (Fig. 7). Here, we used again the blue laser diode as excitation source in order to minimize any absorption of the excitation light in the top p-layer, although such losses cannot be completely disregarded. Indeed, the PL intensity of the QW structure is about 3 times brighter than the intensity of the LED test structure. This may indicate some degradation of the QWs in the LED structure

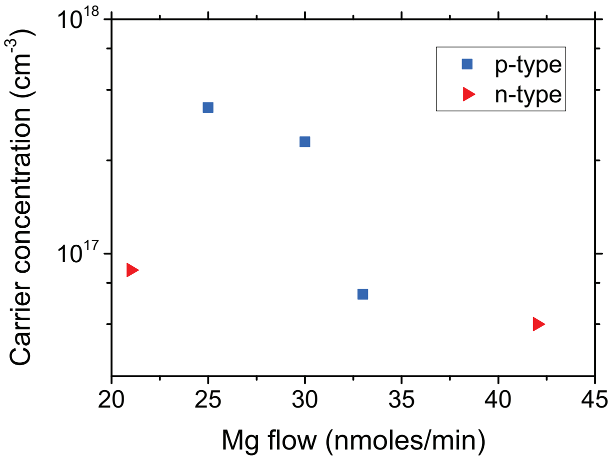

Fig. 5: Carrier concentration measured by the van der Pauw Hall method on Mg-doped test structures at room temperature versus Mg flux. We obtained p-doping only between about 24 and 35 nmol/min Mg flux.

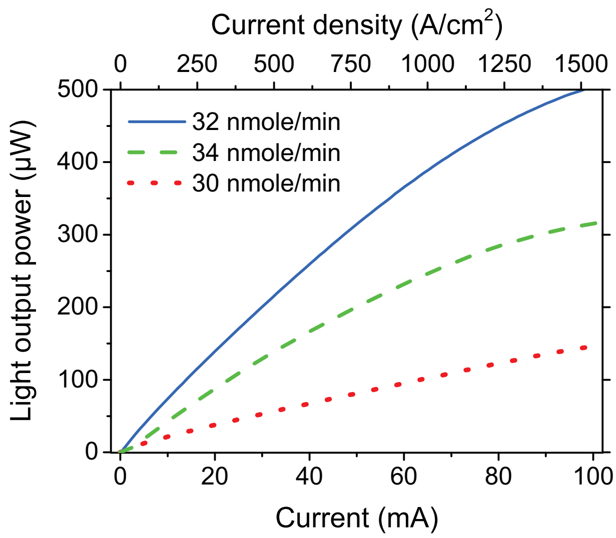

Fig. 6: Electroluminescence intensity versus applied current at room temperature for three different Mg flows during p-GaN growth. Owing to our small p-contact size, fairly large current densities have been obtained (top axis).

by the overgrowth of the QWs by the p-layer grown at 910 °C. Owing to the fairly large In content in these green light emitting QWs of about 30 %, this may be indeed reasonable. However, this does not explain completely the poor performance of our LEDs. Therefore, we think that also the pn junction must be further optimized, particularly by reducing the strong parasitic oxygen doping in our semipolar GaN further.

5. Conclusion

We have carefully evaluated the photoluminescence and electroluminescence efficiency of semipolar GaInN quantum wells grown on patterned sapphire wafers. We found a

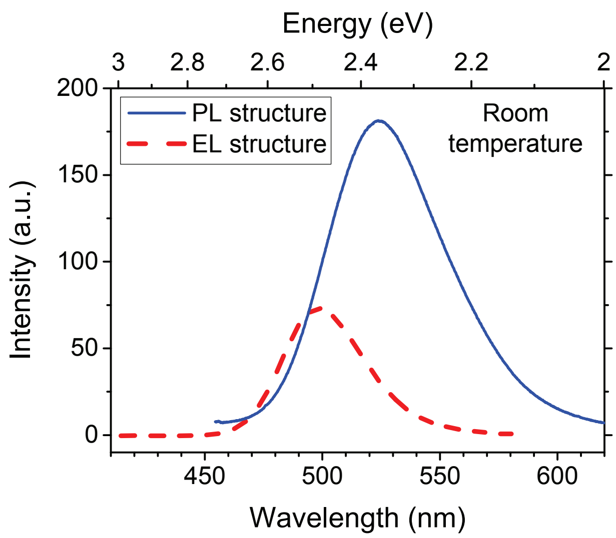

Fig. 7: Photoluminescence measured under comparable conditions on a QW and a LED test structure at room temperature.

fairly large ratio between room temperature and low temperature photoluminescence on samples which do not contain a p-doped top layer. From these data, we can estimate an internal quantum efficiency of about 20 %. However, LED test structures show fairly weak electroluminescence indicating a wall plug efficiency below 0.25 %. When comparing PL and EL data measured on various samples, we suppose that this strong discrepancy is partly a consequence of some degradation of the high In content quantum wells during the p-layer overgrowth. However, a further optimisation of the p- and n-type doping profiles seems to be even more important.

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