MRS Internet Journal of Nitride Semiconductor Research

Volume 2, Article 44

GaN based LED's with different recombination zones

M. Schauler, C. Kirchner, M. Mayer, A. Pelzmann, F. Eberhard, Markus Kamp , P. Unger, K. J. Ebeling
Abteilung Optoelektronik, Universität Ulm

This article was received on June 15, 1997 and accepted on October 8, 1997.

Abstract

GaN based homo- and heterotype LED's have been fabricated and characterized which emit in the blue and ultra-violet part of the spectral range. Complete epitaxial LED layer sequences with different recombination zones have been grown using MOVPE as well as MBE. Subsequent to the material growth, chemically-assisted ion-beam etching and contact metallization are utilized to achieve full LED devices. MBE-grown homotype LED's reveal a peak in the output light spectrum at a wavelength of 372 nm with a linewidth being as narrow as 12 nm. GaN/InGaN LED's grown by MOVPE show visible single peak emission with linewidths of 23 nm. The optical output power as measured in a calibrated Ulbricht sphere is in the 1 µW regime.

1. Introduction

In recent times, there has been increasing interest in light-emitting diodes (LED's) which emit in the visible spectral range from green to blue [1]. Such devices are key components for LED-based full-color displays that are going to become a significant market over the next years. Another interesting application will be the conversion of blue or UV radiation from GaN-based LED's into virtually any color by phosphors or organic dyes. Particularly white LED'sare expected to gain a reasonable share of the illumination market because LED's are smaller, much more robust, and live about 50 times longer compared to ordinary light bulbs [2].

For the present work on GaN LED's, two major growth techniques, molecular beam epitaxy (MBE) and metalorganic vapor phase epitaxy (MOVPE) are employed. Whereas the MOVPE approach is a rather standard one, the MBE approach is somewhat particular, since it uses the ammonia dissociation on the growing surface to provide the atomic nitrogen [3]. Processing and characterization of the devices are performed under identical conditions. Differences in the device performance can therefore be attributed to the vertical structure of the LED.

We will emphasize the role of a recombination zone in order to obtain single wavelength emission from the devices. For this purpose we investigate homojunction LED's without recombination zone (MOVPE), homojunction devices with an undoped recombination zone (MBE), and heterotype InGaN/GaN LED's with an InGaN recombination zone (MOVPE).

2. Experimental

In the following, we briefly describe the growth process for GaN using either MBE or MOVPE, the processing of the structures to full devices, and the characterization methods employed. All GaN structures are grown on c-plane oriented sapphire. Both growth methods make use of a low-temperature GaN nucleation layer, where the actual parameters of deposition are optimized individually. The structures in general consist of approximately 1µm of n-type GaN topped by 0.5 µm to 1 µm of p-type GaN. For the homotype MBE-grown LED, an additional 50-nm-thin undoped recombination zone is inserted between n- and p-type material. The recombination zone for the heterotype MOVPE LED consists of a 50-nm-thick $In_{0.15}Ga_{0.85}N$ layer.

For MOVPE growth, a horizontal reactor (AIXTRON AIX 200 RF) is operated at low pressure. Trimethylgallium (TMGa), trimethylaluminum (TMAl) and trimethylindium (TMIn) are used as group-III precursors. The group-V element, nitrogen, is delivered by ammonia and hydrogen is used as carrier gas. n- and p-doping are achieved by the use of silane (SiH_4) and bis-cyclopentadienylmagnesium (Cp_2Mg), respectively. The growth of GaN is performed at temperatures ranging from 1020 °C to 1060 °C. After a thermal p-activation step, i.e. annealing in nitrogen ambient at 750 °C for 15 min, the material is ready for processing.

The MBE samples are grown in an almost standard MBE system (Riber MBE 32) which has been adapted to group-V gas sources. NH_3 is introduced into the growth chamber through a standard high-temperature gas injector (Riber HTI 432). The decomposition of NH_3 is carried out with an on-surface-cracking technique, where the ammonia molecules are thermally dissociated on the growing surface [3]. Elemental Ga, Al and In are supplied by effusion cells. The crystal itself is grown at a temperature of approximately 720 °C. An activation of the acceptors is not necessary.

Identical processing steps are applied to MBE- and MOVPE-grown material. In the first photolithographic step, the mesa structure is defined. Using a conventional photoresist mask, the pattern is transferred into the semiconductor by chemically-assisted ion-beam etching (CAIBE) thereby creating steep side walls. With gas flows of 6 sccm Ar in the ion source and of 4 sccm Cl_2 in the ring nozzle above the substrate, an etch rate of 70 nm/min is achieved. Subsequently, the samples are boiled in acetone, isopropanol, and methanol to remove all organic depositions from the surface. The n-contact areas are defined by the second lithographic step. The contact itself is made by lift-off technique and consists of 30-nm-thick Ti strengthened by a 150-nm-thick Au layer. The final photolithographic process is the p-contact metallization. For contact formation, 20 nm of Ni and 150 nm of Au are deposited. A schematic illustration of the fabrication sequence depicting the different steps of processing is shown in Figure 1. After dicing with a diamond saw, the LED's are placed into carriers, bonded, and sealed with a transparent resin.

3. Results

A typical IV characteristics of a LED is shown in Figure 2. Turn-on voltages of the devices are between 2.5 and 3 V; breakdown occurs at a reverse voltage of approximately 8 V. A series resistance of 60Ω can be deduced from the IV characteristics, which is comparable to the values of commercially available devices. The specific contact resistance is determined using circular transmission-line structures [4]. On p-type GaN with $p \approx 1 \cdot 10^{17}$ cm^{-3}, a value of $1 \cdot 10^{-2}$ Ω cm^2 for Ni/Au contacts is achieved. On n-type material with free electron concentrations of about $n \approx 1 \cdot 10^{19}$ cm^{-3}, specific contact resistances are in the 10^{-5} Ω cm^2 range for Ti/Au contacts.

Homotype LED's fabricated from MOVPE material feature emission spectra as shown in Figure 3. A relatively broad electroluminescence (EL) band with the two emission peaks gives the LED a bluish-white appearance, which additionally varies with current since the relative intensities of the peaks change. At lower current densities, the maximum intensity occurs at a wavelength of about 440 nm. Such an emission can be attributed to the Mg related transitions which is also observable in photoluminescence (PL) spectra at 300 K. At higher current densities Figure 3 reveals the dominance of the emission at 380 nm. This is in accordance to S. Nakamura's observations [5] who found a similar behavior for his homotype GaN LED's in case of a non-perfect p-doping.

LED's featuring a separate recombination zone behave differently as can be observed in the single peak spectra shown in Figure 4 and Figure 5. The MBE-grown homotype LED which contains the above mentioned 50-nm-thick undoped recombination zone, reveals a narrow electroluminescence linewidth with a full-width at half-maximum (FWHM) value of only 12 nm at a peak wavelength of 372 nm when operated at a driving current of 20 mA (Figure 4). A variation of the current from 25 mA to 40 mA results in a very small shift of the emission peak from 368 nm to 374 nm. No indication of Mg-induced recombination, neither at 430 nm nor at 380 nm, is observed in the EL spectra. Only one radiative transition path is prominent in this structure. From the energetic position, it can be derived that the light generation occurs in the undoped GaN region between p- and n-type material. The difference in the peak PL emission at a wavelength of 364 nm related to the free exciton transition and the EL emission peak at 368 nm is probably due to ohmic heating. Since the light generated in the intrinsic region of the junction is absorbed in the p- and n-doped cladding layers, the lineshape reveals a sharp decrease at the high energy side and a broader tail at the low energy side of the spectrum which also leads to a reduction in linewidth.

GaN/InGaN/GaN double heterostructure LED's grown by MOVPE reveal emission spectra as shown in Figure 5. The device features single peak emission at a wavelength of 392 nm with a FWHM linewidth as small as 23 nm. Even at high driving current densities, an intrinsic GaN peak can barely be detected in the spectrum and the Mg-related long wavelength tail is not present. The wavelength shift caused by driving current variation is negligible. PL measurements on a sample with an InGaN layer embedded in undoped GaN grown under identical conditions show a transitions at at an emission wavelength of 401 nm, proving that recombination takes place in the InGaN layer of the LED.

A comparison of the EL spectra obtained from the different LED's reveals striking differences which are attributed to the vertical structures rather than to the different growth techniques. The standard homotype pn-junction (Figure 3) is similar in almost every feature (lineshape, linewidth, current dependence, peak positions, etc.) to results obtained by Nakamura [5] for p-doping of about $1 \cdot 10^{17}$ cm^{-3}. With introduction of an intrinsic GaN layer (Figure 4), the transitions at 440 nm and 380 nm are no longer present, indicating that the electron-hole recombination does not occur in the Mg-doped part of the junction, but in the intrinsic region. This leads to single peak emission and a significant reduction of the linewidth, however, the structure suffers from internal absorption. Since the observed small linewidth of 12 nm is partially caused by the absorption mechanism, this feature can not be compared to results obtained with LED's where no internal absorption occurs. Substitution of the intrinsic GaN recombination layer with InGaN provides an improved carrier confinement and avoids internal absorption (Figure 5).

The optical output power of the LED's has been measured with a calibrated Ulbricht sphere. For the MOVPE-grown homojunction LED (Figure 3) a saturation occurs at a power level of about 0.7 μW and a corresponding driving current of 30 mA. Under comparable conditions we do not observe a saturation for the MBE homojunction with recombination layer (Figure 4). However, the output power is lower (0.4 μW at 25 mA) because a significant part of the generated light is absorbed in the cladding layers.

Lifetime measurements have been performed with the MOVPE-grown homotype LED by monitoring the optical output power at a constant driving current versus time. A 1 db loss in output power is a commonly used failure criterion. Assuming an exponential decrease in output power over time, the described LED passes industrial requirements for more than 4500 h of continuous operation at room temperature.

4. Summary

GaN LED's with different recombination zones have been fabricated using MOVPE as well as MBE growth. Emission spectra of homojunction LED's show a shift in the peak emission wavelength with operating current that can be attributed to a second recombination path predominant at high current densities. MBE-grown homotype LED's featuring an undoped GaN layer as recombination zone exhibit a narrow emission linewidth (12 nm) at a single wavelength. Therefore, they are suitable pump-light sources for luminescence-converting devices using phosphors or organic dyes. MOVPE double-heterostructure LED's show single peak emission from an InGaN recombination zone. Emission at 392 nm with a narrow linewidth (FWHM 23 nm) is demonstrated for this InGaN/GaN LED. The optical output power of the devices is in the 1 μW regime and is still subject to improvement.

References

[1] Shuji Nakamura, Takashi Mukai, Masayuki Senoh , *Appl. Phys. Lett.* ***64***, 1687-1689 (1994).

[2] P Schlotter, R Schmitt, J Schneider, *Appl. Phys. A* ***64***, 417-418 (1997).

[3] M. Kamp, M. Mayer, A. Pelzmann, K. J. Ebeling, *Mater. Res. Soc. Symp. Proc.* ***449***, 161-172 (1997).

[4] GK Reeves, *Sol. St. Electr.* ***23***, 487-490 (1980).

[5] S. Nakamura, T. Mukai, M. Senoh, *Jpn. J. Appl. Phys.* ***30***, L1998 (1991).

https://doi.org/10.1557/S1092578300001708 Published online by Cambridge University Press

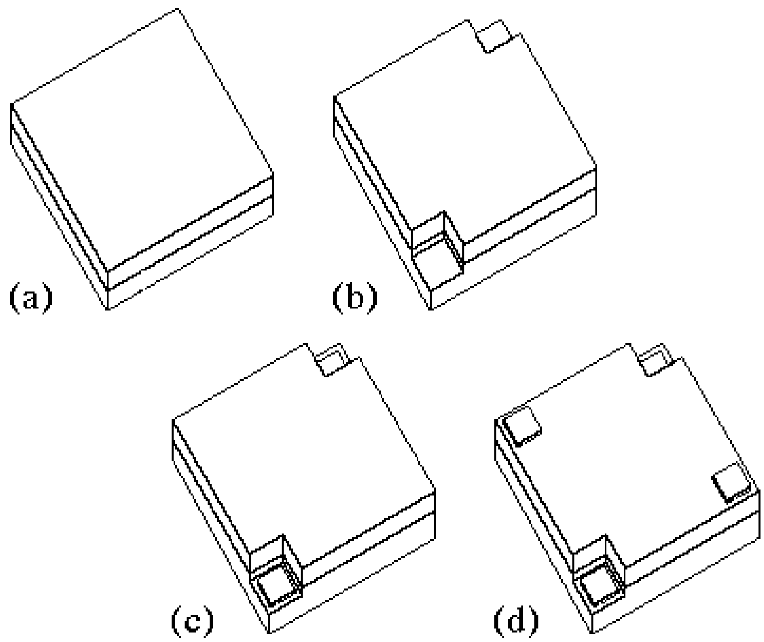

Figure 1. Fabrication steps for GaN-based LED's: (a) after epitaxial growth, (b) after mesa etching using chemically-assisted ion-beam etching, (c) after n-contact metallization, and (d) after p-contact metallization.

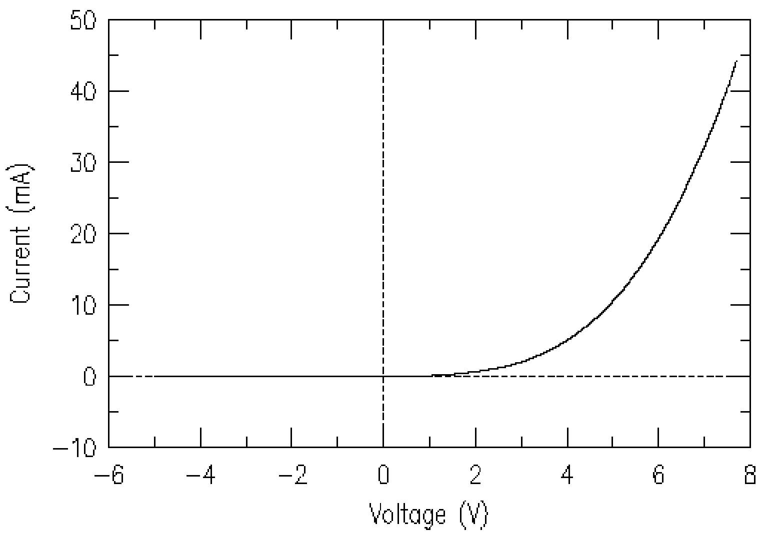

Figure 2. IV characteristic of a homotype MOVPE-grown LED. Typical devices exhibit turn-on volages between 2.5 and 3 V, breakdown voltages of approximately 8 V, and series resistances of 60 Ω.

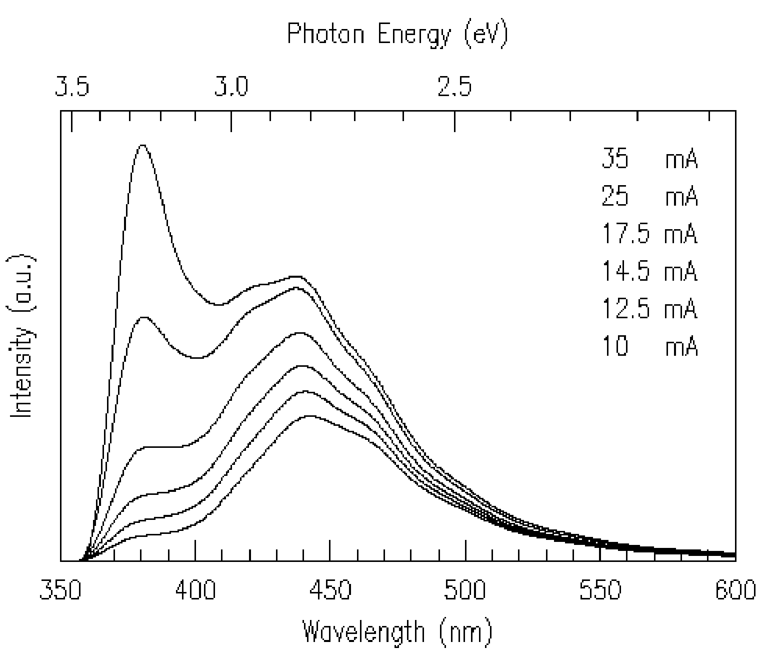

Figure 3. Electroluminescence spectra of a homotype MOVPE-grown LED at different driving currents. Relatively broad electroluminescence ranges are observed. The peak emission at a wavelength of 440 nm (Mg related transitions) for low driving currents shift towards 380 nm for high current densities.

https://doi.org/10.1557/S1092578300001708 Published online by Cambridge University Press

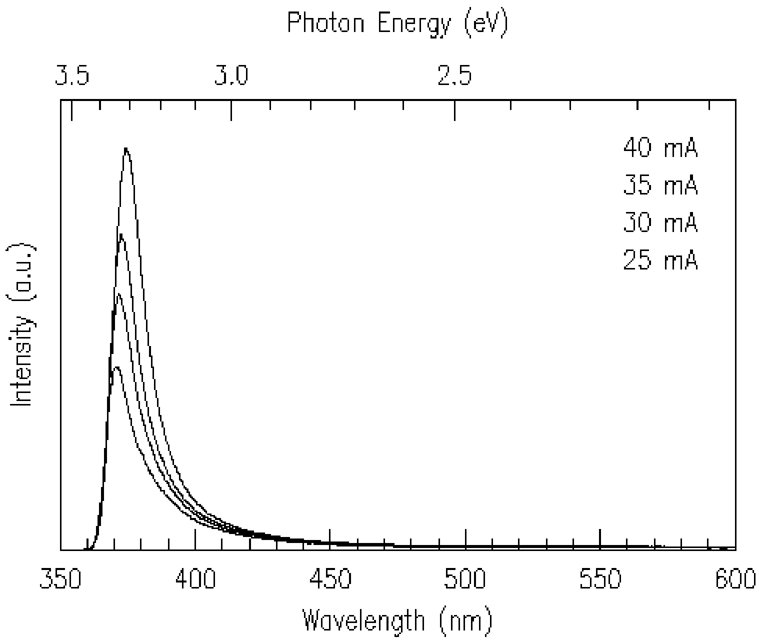

Figure 4. Electroluminescence spectra of a homotype MBE-grown LED featuring an undoped recombination layer at different driving currents. A FWHM linewidth of only 12 nm at a peak wavelength of 372 nm is observed.

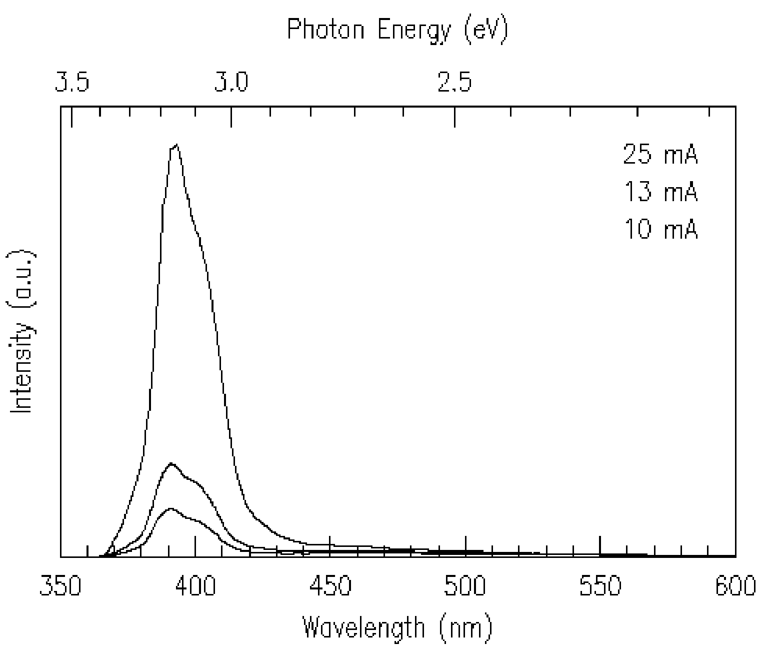

Figure 5. Electroluminescence spectra of a heterotype MOVPE-grown InGaN/GaN LED at different driving currents. Due to the heterostructure, the emission peak is shifted towards longer wavelengths (392 nm) having a FWHM linewidth of 23 nm.

M R S Internet Journal of Nitride Semiconductor Research

https://doi.org/10.1557/S1092578300001708 Published online by Cambridge University Press