High power UVB light emitting diodes with optimized n-AlGaN contact layers

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The development of efficient (In)AlGaN-based LEDs emitting in the ultraviolet B (UVB) spectral region (280–320 nm) is essential to leverage their vast commercial potential. UVB LEDs are expected to not only replace traditional mercury lamps in applications such as curing of polymers and phototherapy but also to establish new applications in the fields of, e.g., medical diagnostics, plant growth lighting and sensing.1,2 Although a lot of progress has been made in the performance of UVB LEDs, the efficiency and operating voltage of the devices as well as their lifetime still needs to be improved.3–5 The main focus for the increase of the internal and external quantum efficiency is usually directed on the reduction of dislocation density,6–8 and thus of nonradiative recombination centers, the optimization of the (In)AlGaN-based multi quantum well (MQW) active regions,9–11 the transparency and doping of the p-side,12–20 the realization of reflective, ohmic contacts21–23 and the enhancement of light extraction. Additional studies about the impact of growth conditions and silicon (Si) doping levels on the conductivity of high Al-containing n-AlGaN layers were done24–30 as well as the identification of the compensating point defects responsible for the observed minimum in resistivity with increasing Si concentration.31–34 Based on these studies the n-doping level of the AlGaN layer was optimized to reach the resistivity minimum of the contact layer. The impact of the Si-doping level on the concentration of compensating point defects in this n-type doping regime was characterized by room temperature photoluminescence (PL). The aim of the study was to find a good compromise between resistance of the n-side, injection of electrons into the active region, i.e. optical output power, as well as the lifetime of the LEDs.

To study the influence of lateral and vertical carrier transport in the Al0.55Ga0.45N:Si n-side it was divided into two parts of different thickness and doping level: a 230 nm thick layer directly below the active region for the vertical injection of electrons into the quantum wells and the underlying 550 nm or 1000 nm thick lateral n-contact layer, responsible for the lateral current transport from the n-metal contact to the area below the active region. The silane flow for both layers was varied in order to achieve low operation voltage together with high output power. Lifetime tests of processed LED structures with different n-doping were carried out.

2. Experimental methods

The LED heterostructures were grown by metalorganic vapor phase epitaxy with standard precursors on 2 inch (0001) oriented sapphire substrates. Templates with 1500 nm AlN grown simultaneously at elevated temperature31,32 in a multi-wafer reactor were employed to ensure similar dislocation densities. These AlN base layers show typical full width at half maximum of X-ray rocking curves (measured with a Panalytical X’PertPro) of 60 arcsec for the (002) reflection and 550 arcsec for the (102) reflection. The corresponding estimated threading dislocation density (TDD)33 is ∼4 × 10⁹ cm⁻². N-type Al0.45Ga0.55N layers for calibration as well as complete LED structures were deposited on these templates at constant growth conditions varying only the silane flow during the n-AlGaN layer growth. The LED structures consist of a 200 nm AlN/GaN short-period superlattice followed by 500 nm undoped Al0.55Ga0.45N, a 3 μm n- Al0.55Ga0.45N:Si buffer, 550 nm or 1000 nm n-Al0.55Ga0.45N:Si as “lateral contact layer”34 and 230 nm n-Al0.55Ga0.45N:Si as “vertical injection layer”; see Fig. 1, grown with different disilane flows at 1086 °C, a V/III ratio of 153 and total pressure of 149 hPa. The active region consists of a threefold InAlGaN/AlGaN MQW for 310 nm emission and is followed by a 16 nm thick Mg-doped AlGaN electron blocking layer,35 a 150 nm thick Al0.45Ga0.55N:Si/MgAl0.32Ga0.68N:Si short-period superlattice and a 20 nm thick GaN:Mg contact layer. For p-type activation the samples were annealed in situ at 890 °C for 15 min in nitrogen ambient. The layer thicknesses were determined from in situ reflectivity data at 405 nm using a LayTec EpicurveTT®. The thicknesses were additionally checked by scanning electron microscopy of cross-sections of LED structures. The n-type doping was realized by different disilane flows. The concentrations of the dopant Si...
as well as that of the impurities O and C were measured in calibration layers grown at different Si flows by secondary ion mass spectrometry (SIMS). The specific resistivity of the calibration layers was determined by Eddy current measurements in an MRes2000d. PL spectroscopy at room temperature was done on calibration samples with a frequency doubled Ar-ion laser with excitation at 229 nm and a power density of about 100 W cm\(^{-2}\) (spot diameter \(\sim 50 \mu m\)).

LEDs were fabricated using standard chip-processing technologies. Mesa structures with a p-contact area of about 0.15 mm\(^2\) were defined by inductively-coupled plasma etching in order to expose the lateral n-AlGaN contact layer. Platinum-based p-contacts and vanadium-based n-contacts were deposited to form the p-electrode and the n-electrode, respectively.

The electrical and optical characteristics of the LEDs were measured on-wafer under direct current injection. For that purpose the wafers were placed epi-side up on a sample holder without any active cooling. The emission spectra and the optical power versus current \((L-I)\) characteristics were measured by collecting the light emitted through the substrate using an optical fiber spectrometer and a calibrated silicon photodiode, respectively.

For the lifetime measurements the wafers were diced into single chips and flip-chip mounted to aluminum nitride ceramic submounts using gold–tin eutectic alloy. Batches of 15 LEDs were attached to a thermoelectric cooler and stressed simultaneously at a constant operation current of 100 mA corresponding to a current density of 67 A cm\(^{-2}\) in the p-contact area at a constant heatsink temperature of 20 °C under air for 100 h. During operation the optical power and drive voltage were measured continuously.

3. Results and discussion

For AlGaN with Al contents below 80% Si behaves as a shallow donor and is the usually employed n-type dopant. It is commonly observed that the resistivity of n-AlGaN:Si layers has a minimum for a Si-doping level near \(2 \times 10^{19} \text{ cm}^{-3}\). Following a decrease of resistivity with increasing Si-doping level it increases again by self-compensation for excessive Si incorporation. To find the optimal IV/III ratio \(A_{0.5}G_{0.5}N:Si\) calibration layers were grown with different disilane flows. Since the resistivity does also depend on the dislocation density of the AlN template, we used AlN/sapphire templates from one multiwafer growth run all showing similar full widths at half maximum of the X-ray rocking curve. In Fig. 2 the resulting specific resistivity \(\rho\) versus the Si concentration are shown. The expected minimum is reached at about 0.012 \(\Omega \text{ cm}\) for a Si concentration of \(\sim 1.7 \times 10^{19} \text{ cm}^{-3}\). There is further potential to reduce the resistivity by reducing the TDD as trapping centers of free carriers. Using the same growth recipe on AlN templates with lower TDD \((1-2) \times 10^{9} \text{ cm}^{-2}\) yielded a resistivity of 0.01 \(\Omega \text{ cm}\) showing the importance of dislocations as also pointed out by Ref. 30. The carbon concentration \([C]\) is about 3 to \(4 \times 10^{17} \text{ cm}^{-3}\) and the oxygen concentration \([O]\) is below \(1 \times 10^{17} \text{ cm}^{-3}\) in the investigated samples. To clarify the source of compensating point defects additionally room temperature PL was carried out. Typical PL spectra of a calibration sample are shown in Fig. 3(a). The spectra are obtained in three measurements with optics adjusted to maximum intensity of (a) the band edge and the defect related peaks at (b) 420 nm (“blue” emission) and (c) 530 nm (“yellow” emission), respectively. This ensures a valid comparison of these different components for different doping levels. The integrated areas below the respective peaks are plotted versus the incorporated Si concentration in Fig. 3(b). It is clearly visible that the intensity of the “blue” emission decreases with higher Si-doping. In literature, this peak is attributed to substitutional carbon on a nitrogen lattice site \((C_N)\) and complexes of \(C_N\) with oxygen. Indeed, AlGaN calibration samples additional grown at lower growth temperature of 1034 °C with the same [Si] of \(1.7 \times 10^{19} \text{ cm}^{-3}\), but with \([C]\) and \([O]\) of \(\sim 10^{18} \text{ cm}^{-3}\) the intensity of the “blue” emission increased by a factor of \(\sim 13\) and the resistivity was higher by a factor of 1.4, demonstrating the importance of carbon as a compensating species. Increasing the V/III ratio the carbon concentration and the “blue” emission could be significantly reduced. The intensity of the “yellow” emission...
increases together with the Si concentration and gets dominant beyond the resistivity minimum, Fig. 3(b). This is in a good agreement to the observations in Ref. 30. This emission is attributed to vacancies of group III (VIII) and complexes of Si with these VIII point defects.30,40) Reference 30 found also an indication, that a high dislocation density triggers the formation of such VIII complexes/defects further. A discussion of the decrease of the formation energy for VIII with higher Si-concentrations can be found in Ref.40. Generally, the intensity of the yellow emission could be reduced by using lower growth temperatures. Thus, PL is a valuable tool for the optimization of growth conditions for minimum resistivity.

To study the influence of lateral and vertical carrier transport in the Al0.55Ga0.45N:Si layer it was divided into two parts: a thick lateral n-contact layer, responsible for the lateral current transport from the n-metal contact to the area below the active region and a thinner layer between the lateral contact layer and the active region for the vertical injection of electrons into the quantum wells. For a better illustration the variants of thicknesses and the Si-concentrations in the calibration layers are illustrated in Table I and Fig. 1. The standard LED structures (Std.) were doped with relatively low Si-levels of $1 \times 10^{19}$ cm$^{-3}$ in the lateral contact layer and $3.8 \times 10^{18}$ cm$^{-3}$ in the vertical injection layer to avoid the formation of point defects near the active region as possible cause of fast degradation of the LEDs. The resulting processed LEDs show relatively high operation voltages of about 7 V at 20 mA in the on-wafer measurements [Fig. 4(a)]. In the next step the Si-doping levels in the n-contact layer and the vertical injection layer were increased to $1.4 \times 10^{19}$ and $1 \times 10^{19}$ cm$^{-3}$, respectively.

![Fig. 3](image1.png)  
Fig. 3. (Color online) (a) Typical photoluminescence spectra of an n-Al0.5Ga0.5N calibration layer. The spectra have been taken with individually optimized detection setup for the spectral regions of the band edge and the deep levels of point defects at 420 nm (blue) and 530 nm (yellow). (b) Integrated intensities of the PL-peaks near the band edge (squares) and of the blue (circles) and yellow (triangles) luminescence as shown in (a) versus n-Al0.5Ga0.5N Si-doping level.

![Fig. 4](image2.png)  
Fig. 4. (Color online) (a) Typical on-wafer current–voltage characteristic of processed LEDs with different n-doping of the lateral contact layer from samples listed in Fig. 1 and (b) operation voltage at 20 mA of samples 1–4 of Fig. 1.

| Sample | Lateral contact layer | Vertical injection layer |
|--------|-----------------------|-------------------------|
|        | Thickness (nm)        | [Si] $10^{19}$ cm$^{-3}$ | Thickness (nm) | [Si] $10^{19}$ cm$^{-3}$ |
| Std.   | 550                   | 0.99                    | 230            | 0.38                    |
| 1      | 550                   | 1.37                    | 230            | 0.99                    |
| 2      | 1000                  | 1.37                    | 230            | 0.99                    |
| 3      | 1000                  | 1.73                    | 230            | 1.37                    |
| 4      | 1000                  | 1.73                    | 230            | 1.37                    |

Table I. Thickness and Si content of lateral n-contact and vertical injection layers in different LED heterostructures (see schematic in Fig. 1), called standard (Std.) and samples 1–4.
(sample 1 in Fig. 4). This reduces the resistivity and, hence causes a significant drop of forward voltage to 5.6 V at 20 mA [Figs. 4(a) and 4(b)]. The influence of an increase of the thickness of the lateral contact layer from 0.5 to 1 μm on the path resistance was proofed with sample 2. The forward voltage reduces slightly to 5.5 V. A further increase of the Si-doping level of the lateral contact layer to $1.7 \times 10^{19} \text{ cm}^{-3}$ in sample 3 decreases the forward voltage again slightly to $\sim 5.4$ V at 20 mA. An increase of the doping level in the vertical injection layer near the active region from 1 to $4.4$ V at 20 mA. The optical output power of the different samples is presented in Fig. 5. The output power increases with the Si-doping level in the lateral contact and/or vertical injection layer. A 1.4 fold increase of output power is found for sample 4 in comparison to the standard sample. The increase of the layer thickness of the lateral contact layer to 1 μm did not result in significant further enhancement of the output power. The higher Si-doping of the n-contact layer reduced the specific n-type series resistivity from 2.1 to $1.7 \times 10^{-2} \text{ Ω cm}$, measured by transmission line structures on the processed LED wafer. That supports the realization of better n-contacts. Here the n-contact resistance was reduced from $5 \times 10^{-2}$ to $3 \times 10^{-3} \text{ Ω cm}$, which leads to a more efficient injection of electrons into the lateral contact layer as well as into the active region. Additionally, lower resistivity yields less Joule heating. While higher Si-doping levels allow for higher output power, the higher concentration of V_{III} revealed in PL could have a negative impact on the lifetime of the diodes. To study this 15 LED chips from each wafer of this series were mounted and then operated at 100 mA (67 A/cm²) and 20 °C for 100 h. The corresponding output power versus operation time (normalized to the value at 0 h) for samples 1, 3 and 4 are shown in Fig. 6. The corresponding starting output powers at room temperature were 4.9 mW (sample 1), 5.6 mW (sample 3) and 6.5 mW (sample 4). After 100 h the mean values of the output power drop to 83% for sample 1, 90% for sample 3 and 95% for sample 4. This shows that the higher Si-doping does not result in faster power degradation but instead in more stable devices. Based on this optimization, LEDs emitting at 310 nm with output powers of up to 26 mW at 350 mA and an extrapolated L70 lifetime of around 3000 h (1000 h measurement without burn-in before stress test) at 100 mA were realized.

4. Conclusions
We have shown, that a careful optimization of the thickness and doping profile of the n-AlGaN electron injection layers underneath the active region has a strong impact on the reduction of forward voltage as well as on the increase of output power of UVB LEDs. The increase of Si-doping up to $1.7 \times 10^{19} \text{ cm}^{-3}$ reduces the resistivity of the n-contact layer without significant increase of the concentrations of deep level point defects. Thus, UVB LEDs with higher output power combined with lower driving voltage and long lifetimes were achieved.

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