Junction temperature analysis in green light emitting diode dies on sapphire and GaN substrates

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1 Introduction

The success of GaN based light emitting diodes (LEDs) in solid state lighting strongly depends on the improvement of light emission efficiency and output power performance in the green spectral range. Yet, a steep drop in the emission power efficiency above 500 nm in these devices still remains unexplained. As the efficiency drops, the loss of electrical input power in the device turns into Joule heating and consequently raises the device temperature. The raised device temperature furthermore limits output power, efficiency, lifetime, the spectral performance, and the reliability of the device. Even though the Joule heating has a direct correlation to the emission performance, there are only very few studies on the junction temperature of GaN based green LEDs.

In this work, our approach is to understand the nonradiative recombination process of GaInN/GaN quantum well (QW) based green LEDs by investigating their associated Joule heating in the active device. The local temperature of LEDs was measured by micro-Raman and photoluminescence (PL) spectroscopy and compared to three dimensional finite element thermal simulations. The dependence of the heat conduction of the substrate material on junction temperature was assessed by analysing the local temperatures of LED dies on sapphire and bulk GaN substrates. In addition, the influence of lateral and vertical heat conduction on Joule heating of the LEDs was studied by comparing the temperature profiles of LED dies of different geometries. By using this data, the spectral performances of the LEDs were evaluated as a function of temperature.

2 Experimental

In this study, four GaInN/GaN QW based green emission LEDs grown on (0001) c-plane of GaN (Ga) and sapphire (Sa) substrates were selected. The LED device structures consisted of five GaInN/GaN QWs sandwiched between n-type GaN on the substrate and a p-type GaN layer grown by metal organic chemical vapor phase epitaxy [1, 2]. In addition, a thin (~20 nm) AlGaN...
electron blocking layer was deposited in between the p-type GaN layer and the QW. (350 µm²) LED structures of mesa area 0.07 mm² fabricated on 2 inch wafers were sliced into dies of variable substrate size. Dies Ga1, Sa1, and Sa2 were fabricated at the center of substrate pieces of areas 9x10 mm², 12x13 mm², 1x3 mm² and thicknesses 400 µm, 430 µm, 330 µm, respectively. Die labelled Sa3 is a thinned single LED die on a 100 µm thick substrate piece. Both samples Sa2 and Sa3 were mounted on copper TO-18 headers. Micro-Raman spectroscopy was performed in z(x,−)z backscattering geometry along the [0001] direction of GaN using a 785 nm solid state laser as the excitation source. The local LED temperature was determined by the peak shift of the GaN E₂(high) phonon mode with respect to its frequency of the unbiased LED. The temperature was deduced using published reference data for the Raman modes [3]. For the photoluminescence (PL) experiment, a 325 nm HeCd laser was used as the excitation source. In the second approach, the temperature was determined from the PL peakshift of the topmost GaN layer of the LED structure. A value for the temperature was obtained using an empirical correlation by Varshni’s and fitting parameters given by Bougrov et al. [4]. Both, Raman and PL measurements were performed at constant drive currents up to 200 mA in increments of 10 mA. The potential for additional heating of the devices by the probe beam was minimized by using a low laser power and short exposure times. Further details about the micro-Raman and PL experiments are given elsewhere [5]. In addition, electroluminescence (EL) as a function of drive current was measured using a calibrated 5 cm spectrometer setup.

Three dimensional finite element thermal simulations of the LED dies was performed using a commercial software package (COMSOL) [6], which solves the Laplace equations for temperature. For the thermal model, conductive, convective, and radiative heat transfer modes were appropriately considered. More details about the thermal simulations including imposed boundary conditions can be found in references [5, 7].

3 Results and discussion The junction temperature of LEDs measured by micro-Raman and PL spectroscopy along with the simulated results are shown in Fig. 1. Here, the temperatures of samples Sa2 and Sa3 were measured both by micro-Raman and PL spectroscopy. Both experimental results show an excellent agreement. This provides a validation of our non-invasive optical techniques of an LED junction temperature measurement. Therefore, the rest of the samples were measured by micro-Raman spectroscopy only. Moreover, three dimensional finite element thermal simulations, in particular for the dies on sapphire substrates (Sa1, Sa2, Sa3), show very similar temperature results. The deviation of the simulated temperature data from the experimental data for sample Ga1, which is grown on bulk GaN substrate, corresponds to the uncertainty of the thermal properties of GaN. The thermal properties of GaN are known to be strongly dependent on the crystalline quality of the material [8].

As shown in Fig. 1, the junction temperatures of four LED dies are nearly proportional to the electrical input power. Thermal resistance values can be deduced from the slope of the graphs. The highest thermal resistance of 428 K/W was for the LED grown on sapphire substrate. The lowest thermal resistance of 63 K/W was observed in the LED grown on thermally better conducting bulk GaN substrate. In addition, the sapphire based LED dies reached a junction temperature as high as 240 °C at a current density of 133 A/cm², while the junction temperature on bulk GaN only reached 83 °C. The significantly higher junction temperature observed in the LED grown on sapphire substrate is mainly associated with the poor thermal conductivity of sapphire. Here, the low thermal conductivity of sapphire is the major barrier to heat removal from the active area of the LED on sapphire. Therefore, thermal energy is strongly trapped in the active region leading to an increase in its temperature. In contrast, the higher thermal conductivity of the bulk GaN substrate allows for better cooling efficiency and consequently a reduced junction temperature. In addition, the higher, non-radiative recombination rate associated with higher dislocation densities in the die on sapphire substrate may also contribute to its higher junction temperature.

![Figure 1](image_url)

Figure 1 Junction temperature of GaN based green LED dies as a function of input electrical power measured by the micro-Raman (dark symbols) and PL (gray symbols) spectroscopy along with the simulated (solid line) junction temperature results.

As observed experimentally and computationally, the local temperature of the LED dies was strongly affected by the geometry of the surrounding substrate material. The large discrepancy in the temperatures between samples Sa1 and Sa2 is evidence of the importance of lateral heat conduction in the substrate. Die Sa1 is located at the centre of a large substrate piece which has a 52 times larger surface area than die Sa2. The larger surface area allows for faster...
heat dissipation along the lateral direction of sample Sa1. This effect is much stronger than the heat dissipation through the copper heat sink of sample Sa2. Hence, the junction temperature of sample Sa1 is much smaller. Samples Sa2 and Sa3 show a similar junction temperature. In these cases lateral and vertical heat conduction compensate each other due to the different surface areas and thicknesses.

Considering the overall good agreement between the experimental and simulated temperature results, our model proves suitable for the design of thermally optimized LED structures and devices.

Figure 2 shows a comparison of the temperature distribution in two hypothetical LED structures (similar to sample Sa2) on 330 µm thick sapphire and GaN substrates. Both substrates are in contact with copper TO-18 headers. Here, as expected from the experimental findings, a lower temperature is observed in the device on GaN substrate. The thermal modelling also shows that the LED junction temperature is strongly affected by the thickness of the substrate. This effect is much pronounced for the dies on sapphire. For example, the model shows that the junction temperature in Sa3 would increase by ~ 33 K if its thickness increases from 100 µm to 425 µm. The same thickness change on GaN substrate will increase the temperature by less than 5 K.

Summarized EL peak position values as a function of Raman interpreted junction temperature are shown in Fig. 3. Each spectrum shows a peak blueshift at low temperature (<360 K) and a redshift at higher temperature. This behavior can be explained by a competition of the quantum confined Stark effect (QCSE) [8] and temperature dependent band gap shrinkage. As the LED drive current increases, due to progressive carrier screening of the piezoelectric field in the QW, the peak position shifts to the higher energy side. On the other hand, as the temperature increases the band gap becomes smaller. At lower temperature, the screening of the piezoelectric field dominates, while at higher temperatures, band edge shrinkage is the dominant contribution.

4 Conclusion We investigated the junction temperature of GaN based green LED dies grown on sapphire and bulk GaN substrates by micro-Raman and PL spectroscopy. Excellent agreement between the different methods confirm the better thermal performance of the LED grown on GaN substrate. Three dimensional finite element thermal simulations show very similar results confirming the suitability of the model for thermal design optimization. We find that the spectral and power performances of the LEDs are strongly perturbed by the Joule heating of the active device.

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References