Junction temperature, spectral shift, and efficiency in GaInN-based blue and green light emitting diodes

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ABSTRACT

The junction temperature of homoepitaxial green and blue GaInN/GaN quantum well light emitting diode (LED) dies is analyzed by micro-Raman, photoluminescence, cathodoluminescence mapping, and forward-voltage methods and compared to finite element simulations. Dies on GaN substrate and sapphire were analyzed under variable drive current up to 200 mA (246 A/cm²). At 100 mA, dies on bulk GaN remain as cool as 355 K (83 °C) while dies on sapphire heat up to 477 K (204 °C). The efficiency droop and spectral line shift in green LEDs with increasing current density can now be separated into electrical and thermal contributions.

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1. Introduction

Progress in epitaxial growth of group-III nitride semiconductors has led to high performing UV, blue, and green light emitting diodes (LEDs) [1,2]. Record devices show quantum efficiencies of 30–40%, while in the green spectral region, efficiencies are typically below 20% [3]. Most of those devices show a reduction of efficiency as drive current densities increase above 10 A/cm². As a result, most of the electrical input power is lost into Joule heating and carrier thermalization. Raised operating temperature in turn is expected to limit output power, device efficiency, device lifetime, and operation reliability. Most GaN-based LEDs are grown heteroepitaxially on lattice mismatched sapphire which results in high dislocation densities of the order of 10⁸–10¹¹ cm⁻² [4]. Higher performance is generally expected from homoepitaxial growth on low-dislocation-density GaN substrate [5]. Fewer dislocations should reduce non-radiative recombination and increase the thermal conductivity of the GaN epi layers [6]. Moreover, a substrate of GaN has a higher thermal conductivity than sapphire and avoids the phonon mismatch and the thermal interface barrier.

In order to understand the role of the junction temperature on LED performance, in terms of light output power, spectral lineshift, and efficiency droop, a direct temperature measurement is needed. Micro-Raman spectroscopy [7,8] photoluminescence (PL) spectroscopy [9], as well as a forward-voltage method [10] have successfully been applied to GaInN/GaN LEDs before, yet here we particularly explore the green emitting and homoepitaxially grown LEDs. GaInN/GaN quantum well (QW) green and — for comparison — blue LED dies grown on GaN and sapphire substrates under variable drive current up to 200 mA (246 A/cm²) are analyzed by micro-Raman, PL, and the forward-voltage method. The temperature distribution across the die was mapped by spatially resolved cathodoluminescence (CL) spectroscopy. Junction temperature results are compared to three-dimensional thermal finite element simulations.

2. Temperature determination

Epi material for six green (G) and blue (B) LED dies labeled G1, G2, G3, G4, B1, and B2 was grown by metal organic vapor phase epitaxy. Dies G1, G2, G3, and B1 have (0001) c-plane sapphire substrates, while B2 and G4 use thick c-plane GaN quasi-bulk substrate prepared by hydride vapor phase epitaxy as provided by Kyma Technologies. G1' and G1 are sister dies from the same wafer. The active region of all the dies consists of five GaInN/GaN QWs with a nominal well width of 3 nm and nominal barrier width of 11 nm embedded in a pn-junction diode. InN fractions reach up to 10% in the blue structures and up to 15% in the green ones. A p-doped AlGaN electron blocking layer of thickness ~20 nm is placed...
between QWs and the highly Mg-doped p-GaN layer. The AlN fraction typically is around 8%. More details can be found in Refs. [2,5]. LED structures of 350 × 350 μm² in size have been fabricated and separated into pieces of variable substrate size. Light output powers range in the 2 to 4 mW in unencapsulated dies at 20 mA. G1 is a die in the center of a substrate piece of area 1 × 3 mm² and thickness 330 μm. G2 is a thinned die of substrate thickness 100 μm with a single active LED structure. Both are mounted on TO-18 copper headers. Dies labeled B1 (6 × 8 mm², 330 μm), B2 (10 × 10 mm², 400 μm), G3 (12 × 13 mm², 430 μm), and G4 (9 × 10 mm², 400 μm) are dies of variable size but identical LED structures fabricated at the center of their substrate pieces (area and thickness are given in parentheses). All processed dies use the same active mesa area of 0.07 mm².

Micro-Raman spectroscopy was performed in z(x,−z)−z backscattering geometry along the [0001] direction of GaN from the top p-layer surface using a Renishaw micro-Raman spectrometer equipped with 785 nm diode laser as an excitation source. A PL experiment along the same sample geometry was performed using a standard PL spectrometer system with 325 nm HeCd laser (3 mW) as an excitation source. CL along the same sample geometry was measured under a 20 keV electron beam in a Joel scanning electron microscope system which connects to a CL spectrometer system. Heating of the sample due to the photo-excitation was minimized by using short time (10 ms) pulse excitation. Spatially resolved CL spectra in lateral steps of 25 μm across the top p-layer surface of die G1 was measured at 50 mA drive current. Unlike the other method, during the CL experiment, the sample was kept in vacuum (10−5 Pa). Both, Raman and PL spectra of selected dies were measured as a function of drive current. As expected, electroluminescence (EL) light output increased with drive current providing an increasing background level for the PL, CL, and Raman signals. This limits the range of useful bias current. Due to their weaker scattering cross section, anti-Stokes Raman measurements were not possible. Raman spectra in backscattering geometry along the c-axis are dominated by the symmetry allowed A₁ (LO), E₂(high), and E₂(low) modes in GaN [11]. The strongest mode is the infrared active E₂(high) mode. The temperature dependence of the peak position in GaN has been determined using the empirical model given by Liu et al. [12]. By referencing to the room temperature data, we account for the different strain states of the structures on either substrate. In the PL and CL experiments, the peak position of the topmost p-GaN band edge emission was monitored. Temperature was derived using a Varshni interpolation of parameters given by Bougrov et al. [13], including micro-Raman, PL, and forward-voltage. The remainder of the heating. Samples G1 and G2 were analyzed by three methods (Fig. 1b). In the CL experiment, in addition, a high energy pass edge filter (E₂∼2.95 eV) was used to suppress strong electroluminescence spectrally (spectra not shown). As the drive current increases, peak positions of the phonon mode and the band edge luminescence shift to the lower energy side. Using Lorentz lineshape fitting, the peak shift was analyzed and interpreted in terms of temperature. Without current bias, E₂(high) is found at 568.7 cm⁻¹ in samples on sapphire and at 566.7 cm⁻¹ in samples on GaN substrate. The difference is due to residual biaxial strain in the GaN on sapphire. The GaN bandedge peak positions of the unbiased die are centered at 3.394 eV.

For the modeling, thermal material parameters of sapphire were used as provided by the manufacturer: thermal conductivity: 42 W/(m K), specific heat capacity: 750 J/(kg K) [15]. For GaN, values vary strongly with the crystalline perfection. A thermal conductivity value of 230 W/(m K) has been reported for a dislocation density of 5 × 10⁹ cm⁻² and it drops to a value of 90 W/(m K) at 10¹⁰ cm⁻² [6]. The bulk samples employed here exhibit a dislocation density of 10⁸ cm⁻² and are doped to an n-type resistivity of 0.5 Ohm cm [12]. Accordingly, we used a value of 177 W/(m K) [16] and 490 J/(kg K) for the specific heat capacity of GaN [17]. Due to the lack of better data, the same values (177 W/(m K) and 490 J/(kg K)) were assumed for the thin layers of AlGaN and GaN in the structure. Metalization layers and the thin silver epoxy die attachment have been neglected in this approach. For the surface of the unpolished copper heat sinks, thin oxide coverage was reasonably assumed by a radiative emissivity of 0.74 [16].

Junction temperatures of the six dies as a function of the electrical input power along with the simulation results are summarized in Fig. 2. The input power was calculated as the product of drive current and applied voltage. In this approach, the radiative emission of EL has been neglected. This is justified by the fact that all dies are bare dies without any light extraction enhancements. As a consequence, generated light, to a high portion, will be reabsorbed within the die and contributes in the heating. Samples G1 and G2 were analyzed by three methods including micro-Raman, PL, and forward-voltage. The remainder of the samples was analyzed by micro-Raman spectroscopy. Between the different methods, we find a good agreement of derived temperature values, which provides a validation of these approaches. The simulation results show good agreement with the experimental ones. A particular detail is the delayed onset and weaker temperature rise in the experimental data of the bulk GaN samples B2 and G4. Apparently, at
low thermal load, heat dissipation is better than simulated. This might be due to finite heat conduction into the header support, finite contribution of lateral metallization and uncertainties about the actual thermal properties of the GaN material in our study. The level of agreement, however, proves the suitability of the thermal modeling.

In all dies, the temperature increase scales with the input power. The strongest increase is observed in green dies (G1 and G2) on sapphire, while the smallest is seen in dies on GaN substrate (G4). At 100 mA (143 A/cm²), the junction temperature in dies on sapphire reaches as high as 477 K (204 °C), while dies on bulk GaN heat only to 355 K (82 °C). From the temperature slopes, effective thermal resistance values for the structures can be derived. We find 428 K/W for dies on sapphire (G2) and 64 K/W for dies on the bulk GaN (G4). According to the simulation results, blue emitting die grown on bulk GaN substrate (B2) shows very similar thermal resistance as G4. Similar thermal behavior in B2 and G4 may relate to dominant thermal cooling effect with GaN substrate. It should be noted here that in the absence of thermal properties of GaN in different content modeling cannot differentiate thermal behavior between G4 and B2. As shown by the thermal simulations, the large discrepancy between dies grown on bulk GaN and sapphire is mainly attributed to the low thermal conductivity of sapphire which acts as a thermal barrier. A second contribution may lie in the variation of the thermal conductivity of the GaN epi layers with defect density. The lower density of threading dislocations, (∼10⁸ cm⁻²) in the homoepitaxial GaN should enhance thermal conductivity over that of GaN on sapphire [6].

The green dies G1 and G2 show a very similar temperature behavior. These two sapphire-based dies have been separated into pieces of different sizes and thickness. The substrate of G2 has been thinned to 100 μm and dies have been diced into (∼350 μm)² pieces. The substrate of G1 has not been thinned (330 μm) and die separation led to larger pieces that include several dies from the mask layout. The larger neighboring epi GaN surface and larger mass of the sapphire results in a larger heat dissipation along the lateral direction. On the other hand, sample G2 loses more heat to the copper heat sink due to the substrate thinning. According to the model, both effects compensate each other explaining the similar junction temperature. The large temperature difference of green dies (G1 and G2) and blue die (B1), all of which are on sapphire, is a consequence of the larger sized substrate in B1.

Using CL spectroscopy mapping of the GaN band edge signal, a two-dimensional temperature map of die G1 is obtained (Fig. 3). According to the map, the junction temperature varies across the die between 86 °C and 120 °C. Due to the metal coverage, no data is obtained in the contact areas including the metalized n-ring surrounding the mesa (not shown). Temperatures obtained here are slightly higher than those of the other methods. This may be due to the absence of convective air cooling in the vacuum of the CL chamber. Besides a few hotspots of elevated temperature, the higher temperature is observed between and near the contacts while the lowest temperatures are found in the areas not connecting the contacts on the shortest route. This must be attributed to non-uniform current distribution in the die and associated Joule heating.

3. Spectral diode behavior

By help of this temperature data, the light output power, efficiency, and spectral performance of the LED emission can now be analyzed in terms of junction temperature. EL of the QW was measured as a function of drive current. The peak position and external quantum efficiency as a function of the Raman interpreted temperature are summarized in Fig. 4. With increasing current, each die first shows a blueshift and then a redshift. For all dies these, the maximum in EL emission occurs above 342 K (69 °C). Heating was provided in three different ways: thermal heating from the outside, internal electrical heating by device operation, and a combination of both. The methods produce different results (see Fig. 5), supporting the notion that several processes are at work. With increasing current, an initial blueshift and subsequent redshift is seen for the dies that are fully and partially heated electrically. The blue shift of purely electrically heated die, at lower current region (I ≤ 60 mA), was found to be varied at a rate of ∼0.5 meV/K. Their wavelength shift reaches a shortest...

![Fig. 2. Experimental (symbols) and simulated (lines) junction temperature values of six LED dies as a function of electrical input power. Data by micro-Raman (solid black), PL (open), and forward-voltage method (gray symbols) is shown. Values of the effective thermal resistance (in kW) are derived from the slopes: G1: 425, G2: 428, G3: 141, G4: 64, B1: 166, and B2: 75.](Image 84x556 to 235x741)

![Fig. 3. The spatial distribution of the junction temperature across die G1 at 50 mA (72 A/cm²) was measured by CL spectroscopy. Shown is the distribution of temperature across the die. No values can be obtained for the p- and n-contacts.](Image 173x176)

![Fig. 4. Variation of the EL peak position as a function of junction temperature. The inset shows the normalized EQE as a function of drive current.](Image 173x176)
The emission wavelength at 519 K and 433 K, respectively. Apparently, unlike the emission of the GaN bandaged, the QW emission in LED operation shifts with a component that is not the lattice temperature. For the thermally heated case, EL was found to redshift only with the temperature at a rate of $\frac{dE}{dT} = -0.23$ meV/K. This can be explained by a bandgap decrease with increasing temperature, as seen before in such LEDs [18]. The significant difference of the initial blueshift can be attributed to the progressing screening of piezoelectric polarization charges within the QWs by the injected carriers. This is commonly attributed to a reduction of the quantum confined Stark effect in the emission wavelength [19,20]. Therefore, the EL peak position of the electrically heated die is controlled by both, the injection current, as well as the junction temperature. Since $\frac{dE}{dT}$ is constant in the given temperature range, the polarization contribution to the EL blueshift is largest at lower currents.

The external quantum efficiency (EQE, defined as the ratio of emitted photons to injected electrons) as a function of drive current is shown in the inset of Fig. 4 (normalized data). All samples show the well-documented performance droop as evidenced by the EQE decrease as current increases. For the sample on bulk GaN, it shows a significantly slower decrease than for the sapphire-based dies. This reveals the dominance of a thermal component in the processes leading to the efficiency droop in those sapphire-based dies. Effective cooling therefore seems imperative for high output performance.

The relative relevance of thermal red shift and non-thermal blue shift is further evidenced by an experiment of mixed die heating. Fig. 5 shows the QW peak emission and the normalized EQE (inset) of die (G1′) as a function of temperature under purely electrical, purely external thermal, and partially external thermal and subsequent electrical heating. For the thermally heated case, QW emission shows a linear redshift and EQE decreases linearly with temperature. In fact, the EQE of purely thermally heated die was reduced to 50% upon increasing its temperature from ambient up to ∼425 K and such behavior is well agreed with the reported temperature dependent efficiency behavior of GaN-based LEDs [21]. For the electrically heated die, the EQE was reduced to 50% at lower temperature at ∼345 K showing faster EQE drop. In addition, when the heating occurs electrically by device operation, the EL emission shows a rapid blue shift and EQE shows a fast drop with temperature. Those behaviors also form the boundaries for the combined heating experiment: when the electrical heating is introduced to the 355 K (82 °C) thermally preheated die, the peak emission switches from its initial redshift to perform an even faster blue shift than the purely electrically heated case. The same holds for the EQE: after an initial decrease commensurate with the thermal heating, it very rapidly decreases to catch up with the purely electrical heated case as soon as electrical operation is turned on. This balance between electrically and thermally induced effects shows that both are of similar relevance in the control of the emission wavelength and the efficiency droop.

The mechanisms behinds the thermally and electrically induced EQE drop are likely the following: with increasing temperature, the kinetic energy of the mobile carriers in the QWs increases. As a result, carriers are more likely to escape from the QW without radiative recombination. On the other hand, under increasing external electrical field, the probability for tunneling of carriers through the tilted barriers of the QW increases [22,23] and injected electrons are more likely to drift through the active layers into the p-side before recombining non-radiatively [24]. Both effects reduce the radiative recombination rate in the QWs and so increase the EQE drop. Therefore, while the first mechanism acts in thermal heating, both together are active under electrical heating. From the different rates of EQE drop with current and under differentiated heating, we estimate that both mechanisms contribute about equally in these dies.

4. Summary

In summary, the junction temperature of blue and green GaInN/GaN LED dies grown on sapphire and GaN substrate has been determined by micro-Raman, PL, and CL spectroscopy as well as the forward-voltage method. We observed significantly better cooling rates in dies on GaN substrate which is attributed to the higher thermal conductivity of GaN. We find the junction temperature of the active device to be strongly affected by lateral heat conduction and dissipation through the surrounding substrate. Finite element thermal simulations of the junction temperature show a good agreement with the experimental results and therefore confirm the thermal model. Optical properties assessed by EL spectroscopy, revealed a blueshift at low and a redshift at high drive currents. These have been described by a competition of charge screening and bandgap lowering the temperature. We find that emission spectra behave very differently under temperature and electric injection. Furthermore, the quantum efficiency exhibits a strong electric injection dependent drop that is of similar extent as the temperature driven losses.

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References


