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Temperature-dependent light-output characteristics of GaInN light-emitting diodes with different dislocation densities

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We have experimentally investigated the temperature dependence of optical-output power of light-emitting diodes (LEDs) with different threading dislocation densities (TDDs) to assess the influence of the TDD on the temperature stability of LEDs. Whereas the LED with high TDD shows a 64% decrease in optical-output power when the ambient temperature increases from 20 to 150 °C, the LED with low TDD shows only a 54% decrease. The temperature dependence of the optical-output power and current dependence of the characteristic temperature T_{ch} of LEDs shows that short radiative recombination lifetime and low TDDs are essential to obtain LED characteristics that are tolerant of high temperatures.

1 Introduction Solid-state light emitters are becoming the dominant light source for applications ranging from low power indicators to high power illumination sources. Especially, backlighting for liquid crystal displays, automotive headlights, and interior and exterior lighting have drawn extensive attention and are making strides toward widespread practical use. The core component for high power solid-state light emitters is a III-nitride-based light-emitting diode (LED) with GaInN well layers. Among the critical LED performance parameters, the temperature of the active region (i.e., junction temperature) is of great importance because it influences many properties of the LED, such as internal quantum efficiency (IQE), device lifetime, color stability, and degradation of packaging materials [1]. For most practical applications, therefore, a low junction temperature is highly desirable and its stability during LED operation is required to maintain consistent LED operating parameters such as operation current, emission wavelength, and optical-output power [2].

An LED characteristic with a weak-temperature dependence of the optical-output power is also highly desirable; this means that the optical-output power of the LED would be tolerant to a wide range of ambient temperatures. High temperature-tolerant LEDs are becoming increasingly important in applications such as automotive headlights where ambient temperatures can be as high as 90 °C. Therefore, it is valuable to investigate the effect of defects on the temperature dependence of optical-output power in LEDs. In this work, we present experimental results along with theoretical estimates of the temperature dependence of optical-output power of GaInN blue LEDs with different defect densities.

2 Experimental procedures The GaInN LEDs used in this study are grown on *c*-plane sapphire using metal-organic chemical vapor deposition. The threading dislocation densities (TDDs) in the GaN templates are controlled by varying nucleation-layer-growth and film-coalescence parameters [3], and are verified after growth using X-ray diffraction (XRD) rocking curve measurements described in Ref. [4]. For the edge-type TDs dominant in typical GaN-on-sapphire templates, it was found that measurements of the TDD by XRD agree with transmission electron microscopy measurements to within a root-meansquare error of ~33%. For consistency, the LED structures are concurrently grown in a multiwafer reactor using n-type GaN-on-sapphire templates with different dislocation densities. The LED heterostructure, characterized by XRD and *in situ* optical reflectance, consists of five 2.4-nm-thick GaInN quantum wells sandwiched between 7.5-nm-thick Si-doped GaN barriers, followed by an undoped GaN spacer layer, a ~30-nm-thick p-type $Al_{0.15}Ga_{0.85}N$ electron-block layer, and a ~400-nm-thick p-type GaN contact layer. The active region emits at a wavelength of 440 ± 5 nm. The indium (In) composition in the quantum wells of different wafers was found to be $15 \pm 1\%$. Devices are processed as mesa structures of $200 \times 200\,\mu m^2$ areas by inductively coupled plasma etching. N-type contacts consist of a Ti/Al/Ni/Au multilayer stack, and a semitransparent NiO/Au contact is applied to the p-type side of the device.

3 Results and discussion Two representative samples – Sample A (Low TDD) and Sample B (High TDD) with measured total TDDs of 5.3×10^8 and $5.7 \times 10^9\,cm^{-2}$, respectively, are investigated. Figure 1 compares the normalized optical-output power of the two samples, at an operation current of 20 mA (pulsed mode, 1% duty cycle, 500 μs pulse width), as a function of the ambient temperature. With increasing temperature, Sample A exhibits a smaller change in the optical-output power than Sample B. At an ambient temperature of 150 °C, the optical-output power of Sample A decreases to 46% of its room temperature value. However, for Sample B, the optical-output power decreases to 36% at the same temperature. This result shows that Sample A has more stable temperature behavior than Sample B. We believe that the gradual decrease of optical-output power with increasing ambient temperature is mainly caused by non-radiative recombination (NRR) via deep levels associated with dislocations. (An effect caused by Auger recombination can be neglected because of the weak temperature dependence of the Auger coefficient.) The recombination of free carriers via deep levels was first analyzed by Shockley, Read, and Hall (SRH) who found that energy levels within the bandgap of a semiconductor are efficient recombination centers; the recombination events of carriers via deep levels are almost always non-radiative processes. Assuming that the trap captures electrons and holes at the same rate, the temperature dependence of the NRR lifetime τ_{NR} of excess carriers in an intrinsic semiconductor is given by [5]

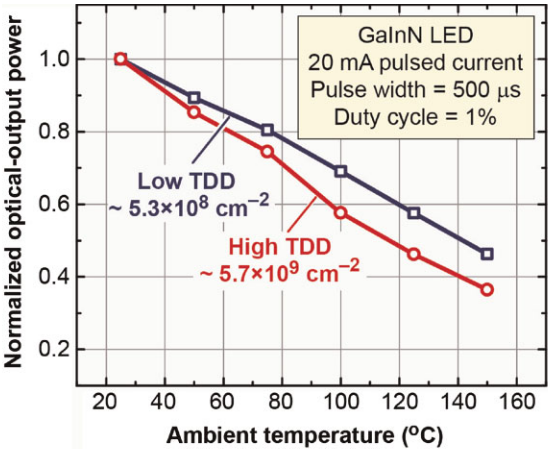

Figure 1 (online color at: www.pss-a.com) Normalized optical-output power of Sample A (low TDD) and B (high TDD) as a function of the ambient temperature at a pulsed forward current of 20 mA.

$$\tau_{NR} = \tau_0 \left(1 + \cosh \frac{E_T - E_{Fi}}{kT} \right), \qquad (1)$$

where E_T and E_{Fi} are the trap energy and the intrinsic Fermi level, respectively. τ_0 is a constant that depends on the concentration of traps and the carrier capture rate. As T increases, τ_{NR} decreases. As a result, the radiative band-to-band recombination efficiency decreases when the temperature increases.

In a previous investigation by Dai et al. [6] that employed photoluminescence, the room temperature NRR coefficient A for Sample A and B was measured to be 6×10^7 and $2 \times 10^8\,s^{-1}$, respectively, and the IQE of Sample A and B was calculated to be 64 and 31%, respectively, at a generation rate of $1.7 \times 10^{26}\,cm^{-3}\,s^{-1}$. To translate those results to the present electroluminescence measurements, we estimate that a similar generation rate is achieved at 20 mA, assuming an active region volume of $5 \times 10^{-10}\,cm^3$ and an injection efficiency of 80%. From these values of the NRR coefficient A, the NRR lifetimes – which are the reciprocal of the A coefficient – for Sample A and B were calculated to be 17 and 5 ns, respectively. From the temperature-dependent measurement of the optical-output power shown in Fig. 1, the IQEs of Sample A and B are calculated to be 29 and 11% at an ambient temperature of 150 °C, respectively. The relationship between IQE, τ_{NR}, and radiative recombination lifetime (τ_R) is given by $IQE = \tau_{NR}/(\tau_R + \tau_{NR})$ [5]. By this equation, the τ_R of both Samples A and B are estimated at about 10 ns and are assumed to be constant over the temperature range under consideration [7]. The τ_{NR} versus the IQE can then be plotted and is shown in Fig. 2. It shows the explicit trend that the IQE and τ_{NR} decrease when the ambient temperature increases. Even though the reduction of IQE for Sample A and B at the ambient temperature of 150 °C is different, with 54% for Sample A and 64% for Sample B, the degree of decrease of τ_{NR} for Sample A and B is almost same, 70% in both cases. This is notable because the decrease of τ_{NR} is dependent only on the temperature and deep level energy difference according to the Eq. (1). The calculated τ_{NR} at 150 °C for Sample A and B are 4.86 and 1.5 ns, respectively. In other words, when the temperature increases from room temperature to 150 °C, even though the relative decrease of τ_{NR} is the same for LEDs with different TDD, the reduction in IQE is different for the two samples because of the non-linearity of the relationship between IQE and τ_{NR}. Sample B (High TDD) shows a very small τ_{NR} of 1.5 ns and this results in a large reduction of the optical-output power at an ambient temperature of 150 °C. This relationship shows that a high

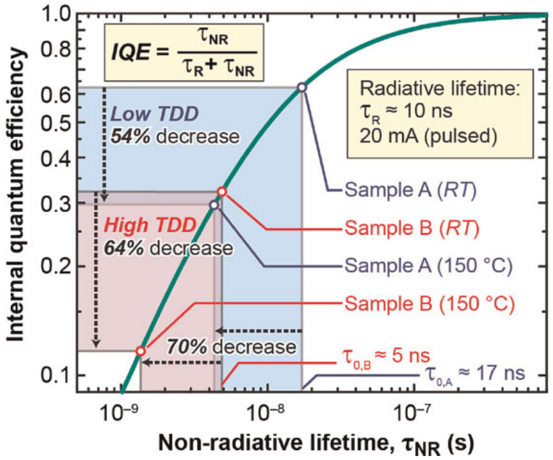

Figure 2 (online color at: www.pss-a.com) IQE versus τ_{NR} as the ambient temperature increases from room temperature to 150 °C for LED Sample A (low TDD) and B (high TDD).

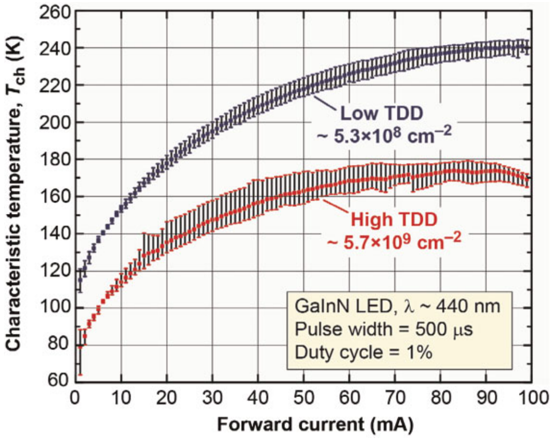

Figure 3 (online color at: www.pss-a.com) Characteristic temperature T_{ch} as a function of current for Sample A (low TDD) and B (high TDD). The error bars represent the variation of T_{ch} as determined from multiple devices on each wafer.

value of τ_0 is required to reduce the effect of temperature on optical-output power, i.e., IQE.

Alternatively, the temperature dependence of the optical-output power (L) can be described by the phenomenological equation [5]

$$L = L_{300\,\mathrm{K}} \exp\left(-\frac{T - 300\,\mathrm{K}}{T_{ch}}\right), \qquad (2)$$

where $L_{300\,\mathrm{K}}$ and T_{ch} are the LED's optical-output power at 300 K and the characteristic temperature, respectively. Generally, a high characteristic temperature T_{ch} implies weak temperature dependence and is always desirable. The reported values of T_{ch} for GaInN LEDs range from 60 to 1600 K at 20 mA [8–10]. We extract T_{ch} from the family of measured optical-output-power versus current curves at different temperatures. Figure 3 shows the T_{ch} as a function of current for multiple devices measured on Sample A and B. First, Sample A shows higher T_{ch} values than Sample B at all measured current ranges. That is, the lower density of NRR centers of Sample A contributes to a more robust characteristic of optical-output power on temperature, as discussed in the previous paragraphs. Second, the T_{ch} gradually increases with increasing current in both samples. T_{ch} of Sample A increases from 115 to 236 K as the current varies from 1 to 90 mA and T_{ch} of Sample B increases from 79 to 169 K for same current change. The dependence of T_{ch} on injection current for GaInN LEDs has not been reported previously in the literature. We believe that the T_{ch} is mainly influenced by the SRH recombination rate, that is, not by the radiative recombination and Auger recombination rates. At low currents, the SRH recombination, among all kinds of recombination channels, dominates the temperature dependence, resulting in a strong temperature dependence (i.e., low T_{ch}). But the effectiveness of the SRH recombination becomes smaller with increasing current, which makes a weaker temperature dependence of the optical-output power in the high current region. Note that the temperature dependence of the optical-output power may not be significantly influenced by radiative recombination and Auger recombination. In addition, we suggest that degraded injection efficiency in the MQWs of LEDs occurring at high currents could be responsible for the reduced temperature dependence of the optical-output power as well as the reduction of the external quantum efficiency [11].

4 Summary We have experimentally investigated the temperature dependence of the optical-output power of GaInN LEDs with different dislocation densities. The LED with low TDD shows a smaller decrease of IQE at high temperature than the LED with high TDD. Both samples show the same relative decrease of NRR lifetime. From the change of the NRR lifetime and the IQE, we determine that low values of the radiative recombination lifetime and low TDDs are essential to obtain LED characteristics that are tolerant of high temperatures.

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