Current and optical low-frequency noise of GaInN/GaN green light emitting diodes

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ABSTRACT

We report on the low-frequency current and light noise in 515 nm green GaInN/GaN quantum well LEDs. The current noise was the superposition of the 1/f and the generation-recombination (GR) noise. The characteristic time of the GR process was found to be proportional to the reciprocal current for the entire current range. This dependence is the characteristic for the monomolecular non-radiative recombination. The dominance of the nonradiative recombination is in agreement with the measured low external quantum efficiency (EQE) <10%. Hence, the noise measurements point out that a low EQE is caused by the low internal quantum efficiency and not by an inefficient light extraction. The noise spectra of light intensity fluctuations were close to the 1/f noise and correlated with the LED quantum efficiency and with the recombination current. Higher noise corresponded to a smaller quantum efficiency and to a higher non-radiative recombination current. The relative spectral noise densities of the light intensity fluctuations within the LED spectral line increase with the wavelength decrease. Fluctuations at different wavelengths are found to be correlated.

Keywords: green GaInN/GaN LEDs, 1/f noise, generation-recombination noise, quantum efficiency.

1. INTRODUCTION

An important advantage of visible LEDs is a highly stable light output with intensity fluctuations smaller than those of incandescent lamps [1-4]. Therefore, GaN/AlGaN and GaN/GaInN light emitting diodes (LEDs) are finding applications as low noise sources in communications, biomedical diagnostics, and in identifying miniscule amounts of hazardous biological and chemical agents [2,5-7].

GaN/AlGaIn and GaN/GaInN quantum wells LEDs cover the wide spectral range from the visible light to deep ultraviolet (UV). However, several groups revealed a discontinuity of various aspects of the spectral emission properties once the emission wavelength extends beyond the values of around 500 nm. Particularly, devices emitting at the human eye's sensitivity maximum perform at roughly only 10% of the performance achieved in structurally very similar blue emitting GaInN/GaN LEDs. Originally, it had been attributed to difficulties of increasing the InN-fraction beyond values of 0.20. This alone, however, cannot be the limiting factor since LEDs emitting at 530 nm can well be produced with InN-fractions below 0.20.

An analysis of the current and optical noise behavior green LEDs holds high promise to reveal both the origin of the noise sources and aspects of the carrier feeding mechanisms involved and their possible distinction from LEDs emitting at shorter wavelengths.

Early publications on the light intensity noise were devoted mainly to the laser diodes [8-12] (with exception of ref.[13]). Recent study of noise in UV GaN/AlGaIn LEDs demonstrated their superior noise characteristics in comparison with other UV light sources [3,4]. Optical noise of the green GaN/GaInN has been studied in Ref. [14]
In the present paper, both, current noise (1/f and generation-recombination) and light intensity noise were studied as a function of the LED current in green GaInN/GaN LEDs. The light intensity noise was measured as a function of the wavelength within the emission spectra of LEDs.

2. EXPERIMENTAL DETAILS.

The samples in this study have been prepared by metal organic vapor phase epitaxy (MOVPE) in an Emcore D-180 SpectraGaN rotating disc multiwafer system using trimethyl and diethyl adducts of Ga, In, Al, as well as ammonia. Ga$_{1-x}$In$_x$N/GaN multiple QW structures have been embedded in (0001) oriented GaN pn-diodes on sapphire substrate. Active region consisting of five Ga$_{1-x}$In$_x$N QWs of nominal well width $L_w = 3$nm, separated by barriers of nominal width $L_b = 11$nm have been grown at temperatures above 650 °C. The resulting $x$-values are in the range of 0.10 to 0.20 as determined by x-ray diffraction analysis. There is no intentional doping in the active region. The n-layers are Si doped to reach free electron concentrations of ~3×10$^{18}$ cm$^{-3}$ and the p-layers are Mg doped to free hole concentrations up to the mid 10$^{17}$ cm$^{-3}$. The final LED dies of 350 μm × 350 μm were mounted on TO-18 header without coating. Further details of the growth have been reported elsewhere [15].

The LED light intensity fluctuations were measured by the UV enhanced Si photodiode UV-100L from UDT Sensors, Inc. biased by a low noise battery using a load resistor, $R_{phds} = 10 - 50k\,\Omega$. To eliminate the contribution of the current fluctuations to the light intensity fluctuations, the LED load resistor was taken to be $R_{LED} = 1k\,\Omega$, which is one to two orders of magnitude higher than the LED differential resistance at high currents.

The dependencies of the differential LED resistance $R_d$ on the LED current, $I_{LED}$, are shown in Fig.1 for three LEDs under study. For all LEDs, these dependencies are close to the $2kT/qI_{LED}$ law at currents up to 0.5mA and deviates from that law only at higher currents ($k$ is the Boltzmann constant and $T$ is the temperature). However, even at $I_{LED}=30$mA, the current dependencies of the resistance do not tend to saturate indicating a dominant contribution of the barrier resistance to the overall LED resistance.

![Fig.1 Dependencies of the differential LED resistance $R_d$ on current for three LEDs. The dashed line shows the resistance $2kT/qI_{LED}$.](image)

For the wavelength resolved noise measurements, the light from the LED was passed through a CM110 monochromator. To insure that the light intensity was high enough for the noise measurements, the optical bandwidth was set to its maximal value of 15 nm.
For the current noise measurements, the LED load resistor varied from 100 Ω to 10 kΩ, depending on the LED current. The voltage fluctuations $S_v$ across the load resistors were measured by a Signal Recovery low noise amplifier (model 5184) and a SR 770 Network Analyzer.

3. RESULTS AND DISCUSSIONS

3.1 Optical Noise

Fig.2 shows spectra of the LEDs under investigation at current $I_{LED}=30$ mA. Multiple fringes seen on the spectra must be attributed to reflection and interference on the air/nitride/sapphire interfaces.

![Optical spectra of LEDs under investigation, $I_{LED}=30$ mA.](image)

Fig.2 Optical spectra of LEDs under investigation, $I_{LED}=30$ mA.

![Current dependencies of the wavelength of the LED maximum power (a) and full width at half maximum (FWHM) of the spectral line (b).](image)

Fig.3. Current dependencies of the wavelength of the LED maximum power (a) and full width at half maximum (FWHM) of the spectral line (b).

The wavelength of the maximum was about 515 nm at high current and decreases with the current increase, see Fig.3a. The full width at half magnitude (FWHM) of the spectral line at room temperature was 30-35 nm, which corresponds to the energy $(5.4-6.4)kT$ (Fig.3b). (The theoretical limit for the FWHM determined by the thermal distribution of carriers...
is $1.8kT_e$, where $T_e$ is effective carrier temperature [16]). As shown in [17], additional line broadening in LEDs might come from a non-homogeneous distribution of the potential within the QW and carriers in different QWs along the LED area. Electron degeneration in the QW at high currents above a few milliamperes also contributes to the line broadening.

Fig.4 shows the spectra of the photodiode current fluctuations (light intensity fluctuations) as a function of forward current for the LED-C. The background noise of the amplifier and thermal noise associated with the photodiode load resistor $R_{phd}=10k\Omega$ are shown for comparison. In this experiment, the LED light was passed directly on the photodiode avoiding the monochromator. As seen, the noise spectra of the light intensity fluctuations for all LEDs were close to the $1/f$ noise with minor deviations, which varied with the LED current. That might indicate weak contributions of the generation-recombination (GR) noise.

![Fig.4 Spectra of the photodiode current fluctuations (light intensity fluctuations) for different LED currents. The background noise and the theoretical thermal noise of the photodiode load resistor are also shown.](image)

Fig.5 shows the current dependence of the relative spectral noise density of light intensity fluctuations ($f=1$Hz) for the three LEDs under study [14]. Typically, the relative spectral density of the noise in GaN-based LEDs decreases with a current increase [1-4]. However, devices “LED-B” and “LED-C” demonstrated unusual behavior having a knee on the noise versus current dependence. This is thought to be due to the possible contribution of GR noise at low currents.

![Fig.5 Dependence of the relative spectral noise density of light intensity fluctuations on current. The frequency of analysis is $f=1$Hz.](image)

The LED current dependence of the external quantum efficiency (EQE) and the current voltage characteristics of the same LEDs are shown in Fig.6 and Fig.7, respectively. Comparing Fig.5, Fig.6 and Fig.7 we see that the higher the EQE, the lower is the noise, and the lower is the current at low bias, where current is determined mainly by the non-radiative
recombination. Therefore, the concentration, \( N_r \), of the recombination centers responsible for the non-radiative recombination appears to be linked to the optical noise. A possible mechanism for the noise are fluctuations of the carriers concentration in the QW and, therefore, fluctuations of the radiative recombination rate. Fluctuations of the carrier concentrations are caused either by the recombination centers itself, or another trap level accompanying the recombination centers.

**Fig.6.** LED efficiency as a function of current.  
**Fig.7.** Current voltage characteristics of the LEDs.

The relative spectral noise density of the light intensity fluctuations as a function of the wavelength within the LED spectral line is shown in Fig.8 for LED-C for two different currents. The spectral lines of the LED are also shown as a reference. Ellipses in figure show the experimental error for both, noise and the wavelength (the last one is due to the optical bandwidth of the monochromator). As seen, noise increases with the wavelength's decrease. All LEDs under study demonstrated a similar dependence of noise versus wavelength.

**Fig.8** Relative spectral noise density of the light intensity fluctuations as function of the wavelength within the LED spectral line for the device C.
The directly measured total light noise can be compared with the wavelength resolved noise spectrum. The summation over all wavelength channels should reproduce the total noise. This integral, however, can be taken in two different ways. Under the assumption that fluctuations at different wavelengths are fully uncorrelated:

\[
S_t = \frac{\int_{\lambda_1}^{\lambda_2} dS_\lambda}{\int_{\lambda_1}^{\lambda_2} dl_\lambda}^2
\]

or fully correlated:

\[
S_t = \left( \frac{\int_{\lambda_1}^{\lambda_2} \sqrt{dS_\lambda}}{\int_{\lambda_1}^{\lambda_2} dl_\lambda} \right)^2
\]

where \(dS_\lambda\) and \(dl_\lambda\) are the spectral noise density and current for the measurements at some particular wavelength.

As seen from the Fig.9, the integral taken assuming correlation at different wavelengths fits the experimental results much better than the uncorrelated summation. Apparently, some mechanism must exist, that synchronizes the light intensity fluctuations across the wide width of emission wavelength.

![Fig.9 Relative spectral noise density of light intensity fluctuations as a function of the current for LED C. Open symbols show the light intensity noise when the entire LED spectrum is included in the noise measurements. Multiple open symbols at \(I_{LED}=30mA\) show results of measurements with different photodiode load resistor and different amount of light collected by the photodiode. Filled symbols are the integrals obtained from the measurements at different wavelength assuming correlated and uncorrelated fluctuations. Filled symbols are shifted left for clarity. The inset shows the current dependence of the relative spectral noise density of the current noise \(S_{I/LED}\).]
The inset in Fig.9 shows the relative spectral noise density of the LED current noise (note that these are not short circuit but actual current fluctuations in the LED circuit with load resistor $R_{LED} = 1 \, \text{k}\Omega$). As seen, this noise is many orders of magnitude smaller than the optical one, and, therefore, cannot explain the correlation of the optical noise at different wavelengths. Note that this correlation cannot be explained either by some external effect, by vibration, for example. First, special precautions have been taken to insulate from any vibration (microphonic noise). Second, a dependence of the noise on the current and a different shape of these curves for different LEDs (see Fig.5) are impossible to be explained by an external source.

Instead, this correlation and the dependence of noise on the wavelength shown in Fig.8 can be explained as follows. Since the FWHM is much higher than the theoretical limit, broadening of the spectral line comes mostly from the non-homogeneous potential within the QW [17]. By other words, different areas of the LED are responsible for the emission at different wavelengths. The fluctuating carriers spread within the quantum well during the characteristic time of the order $d/v_F$, which is much shorter than $1/2\pi f$ where $f$ is the frequency of noise measurements, $v_F$ is the velocity on the Fermi level, and $d$ is the diameter of the LED. Therefore, fluctuation of the carrier fluctuations in some particular part of the area “rapidly” spread to the whole LED and cause a simultaneous change in the light intensity at different spots (at different wavelengths). This can explain why the noise at different wavelengths is correlated.

The fluctuating carriers affect the concentration at the Fermi level much stronger than the states well below it. Radiative transitions from the Fermi level contribute to the short wavelength side of the emission and transitions from states below the Fermi level are responsible for the longer wavelength side. Therefore, the noise at shorter wavelength is stronger than at longer wavelength.

### 3.2 Current Noise

Fig.10 shows the normalized noise spectra $(S_{LED}^{I} f)$ of the LED short circuit current fluctuations at different current levels. As seen, the noise is a superposition of the $1/f$ and the GR noise, which reveals itself as maxima in Fig.10. In contrast to findings in Ref. [4], a non-monotonic dependence of the noise was not found. The characteristic time of the GR noise $\tau_0 = 1/2\pi f_0$ decreases with the current increase ($f_0$ is the frequency of maxima in Fig.10).

![Normalized noise spectra](image)

Fig.10 Normalized noise spectra $(S_{LED}^{I} f)$ of LED current fluctuations at different currents for LED C.

The current dependence of the characteristic time $\tau_0 = 1/2\pi f_0$ is shown in Fig.11. Let us assume that the GR noise is caused by one type of carriers, for example, by electrons. Then the characteristic time of the GR noise is a combination of the capture $\tau_c = (\sigma v)^{-1}$ and emission $\tau_e = \sigma v N_c \exp(-E_t / kT)$ times: $\tau_0^{-1} = \tau_c^{-1} + \tau_e^{-1}$ where $\sigma$ is the capture cross section, $v$ is the thermal velocity (or the Fermi velocity), $N_c$ is the effective density of states and $E_t$ is the energy position of the trap. Since only the capture time depends on concentration, i.e. on current, we conclude that the capture time dominates the GR process. For the monomolecular recombination, the current is $I_{LED} = n$. Therefore, in this case, we
expect $\tau_0 \sim 1/\text{ILED}$. Since the experimental dependencies of the characteristic time $\tau_0$ are close to this law (see Fig.11), we conclude that GR noise comes from the QW and that monomolecular recombination dominates.

This conclusion agrees with the relatively low quantum efficiency of these LEDs (see Fig.6). Hence, the noise measurements point out that a low EQE is caused by the low internal quantum efficiency and not by an inefficient light extraction.

The dependence of the $1/f$ noise on current is shown in Fig.12. This dependence is close to the $S_{\text{LED}} \sim I_{\text{LED}}$, which is typical for the noise that originates in the barrier resistance in contrast to the noise from the contacts or from the unmodulated neutral parts of the diode (see Ref. [18] and references therein). This is in agreement with a dominance of the barrier resistance even at high currents (see Fig.1.).

4. CONCLUSIONS

The optical, i.e. light intensity, and current low-frequency noise were studied in green GaInN/GaN QW light emitting diodes. The noise spectra of light intensity fluctuations were close to the $1/f$ noise. We found that the optical noise is correlated with the LED quantum efficiency and with the level of the recombination current. In particular, the higher the noise, the smaller is the quantum efficiency and the higher is the recombination current. That observation allowed us to conclude that the optical noise is linked to the non-radiative recombination centers. The low frequency optical noise was measured as a function of wavelength inside the spectral line of the LEDs. It was found that the relative spectral noise densities of the light intensity fluctuations within the LED spectral line increases with the wavelength decrease. Fluctuations at different wavelength are found to be correlated. This is thought to be a result of the fast spreading of fluctuating carriers along the quantum wells.

The noise spectra of the current noise were found as a superposition of the $1/f$ and the generation-recombination noise. The current dependence of the characteristic time of the generation-recombination noise and current dependence of the $1/f$ noise indicate that this noise comes from the quantum wells where the nonradiative recombination is dominant.

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