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Wavelength-resolved low-frequency noise of GaInN/GaN green light emitting diodes

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Light intensity low-frequency noise was studied in green GaInN/GaN quantum well light emitting diodes. The light intensity noise was measured as a function of wavelength within the light emitting diode spectral emission line. The spectral noise density is found to increase with decreasing wavelength. Comparing the wavelength-resolved noise with the total light noise, we found that the emission intensity fluctuates synchronously across the entire linewidth. The source of this noise can be ascribed to nonradiative recombination centers. © *2006 American Institute of Physics*.

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I. INTRODUCTION

The radiative recombination processes in group-III nitride heterostructures remain the subject of continued investigation in order to increase performance of high brightness light emitting diodes (LEDs) in the ultraviolet (UV), blue, and green spectral regions.[1,2] In particular, green LEDs employing active regions of GaInN/GaN quantum wells (QWs) reveal a strong drop in emission power performance when the emission wavelength is being extended beyond 500 nm. Devices emitting at the human eye's maximum sensitivity perform at roughly only 10% of the performance achieved in structurally very similar blue emitting GaInN/GaN LEDs. Overall efficiency and performance hold significant promise for substantial improvement for all solid state lighting once the limiting factors have been identified.[3,4] Understanding and mitigating the factors limiting the LED's performance at this wavelength, are therefore very important.

In principle, extending the emission wavelength from 365 nm to higher wavelength should be possible by a mere increase of the InN fraction in GaInN/GaN QWs. Optical spectroscopy by many groups, however, reveals a discontinuity of various aspects of the spectral emission properties and device performance aspects once the emission wavelength extends beyond the values of around 500 nm. 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. Determining the nature of the radiative transition responsible for the light emission in the green must considered a major advancement towards any further performance enhancement.

To this end, an analysis of the noise behavior of the light in green LEDs holds high promise to reveal aspects of the carrier feeding mechanisms involved and their possible distinction from LEDs emitting at shorter wavelengths.

Low-frequency noise of the light intensity and current of laser diodes and LEDs were studied in multiple publications (see Refs. 5–13 and references therein). Different noise mechanisms were found for the light intensity and current noise below and above the lasing threshold. Study of the noise in visible and ultraviolet LEDs showed their superior noise characteristics in comparison with other light sources.[11–13] Several publications dealing with current fluctuations in LEDs have shown that the low-frequency current noise can be used to study degradation phenomena in semiconductor and organic LEDs.[14–16] In the present paper the light intensity fluctuations were studied both for the total light noise and as a function of the wavelength within the emission spectra of GaInN/GaN green LEDs.

II. EXPERIMENTAL DETAILS

The samples in this study have been prepared by metal organic vapor phase epitaxy (MOVPE) in an Emcore D-180 SpectraGaN rotating disk multiwafer system using trimethyl and diethyl adducts of Ga, In, Al, as well as ammonia. $Ga_{1-x}In_xN$/GaN multiple QW structures have been embedded in (0001) oriented GaN p-n diodes on sapphire substrate. Typical design parameters for the active region are as follows: Five $Ga_{1-x}In_xN$ 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 result-

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ing 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 $\sim 3\times 10^{18}$ cm^{-3} and the p layers are Mg doped to free hole concentrations up to the mid-10^{17} cm^{-3}. Samples are characterized at various stages of the process, i.e., prior to deposition of a p side, the full p-n structure in epiform, fully processed and separated bare die mounted on TO-18 header without coating. The final LED dies are 350×350 μm^2 along the edges. LED structures have previously been identified by their low V-defect density (3.6×10^8 cm^{-2}) and smooth surface growth morphology (0.14 nm rms roughness) of the last barrier in the active region. Further details of the growth have been reported elsewhere.[17]

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 in series with a load resistor $R_{\text{phd}}=10-50$ kΩ. To eliminate the contribution of the current fluctuations to the light intensity fluctuations, the LED load resistor was taken to be $R_{\text{LED}}=1$ kΩ, which is one or two orders of magnitude higher than the LED differential resistance at high currents.

The voltage fluctuations S_v across the load resistor were measured by a Signal Recovery low noise amplifier (model 5184) and a SR 770 Network Analyzer. For the wavelength-resolved noise measurements, the light from the LED was passed through a CM110 monochromator. To ensure that the light intensity was sufficient for the noise measurements, the optical bandwidth was set to 15 nm. The experiments were performed for three LEDs, which differed in noise and external quantum efficiency (EQE).

III. RESULTS AND DISCUSSIONS

The noise spectra of the light intensity fluctuations 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.

Figure 1 shows the current dependence of the relative spectral noise density of light intensity fluctuations ($f=1$ Hz) for the three LEDs under study. Typically, the relative spectral density of the noise in GaN-based LEDs decreases with a current increase.[11–13] However, 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.

Figure 2 shows the EQE as a function of current. Comparing Figs. 1 and 2 we see that the higher the EQE, the lower the noise. Since higher EQE means smaller contribution of the nonradiative recombination, we conclude that the concentration of the nonradiative recombination centers, N_r, appears to be linked to the optical noise. This conclusion is confirmed by the analysis of the current-voltage characteristics shown in Fig. 3. At low voltages the current is determined by the nonradiative recombination. As seen at $V<2.5$ V this current is higher for the LED with smaller EQE and higher noise (LED-C) and it is smaller for the LED-A, which demonstrated higher EQE and smaller noise. A possible mechanism for the noise is fluctuations of the carrier concentration in the QW and, therefore, fluctuations of the radiative recombination rate. Fluctuations of the carrier concentrations are caused either by the recombination center themselves or by another trap level accompanying the recombination centers.

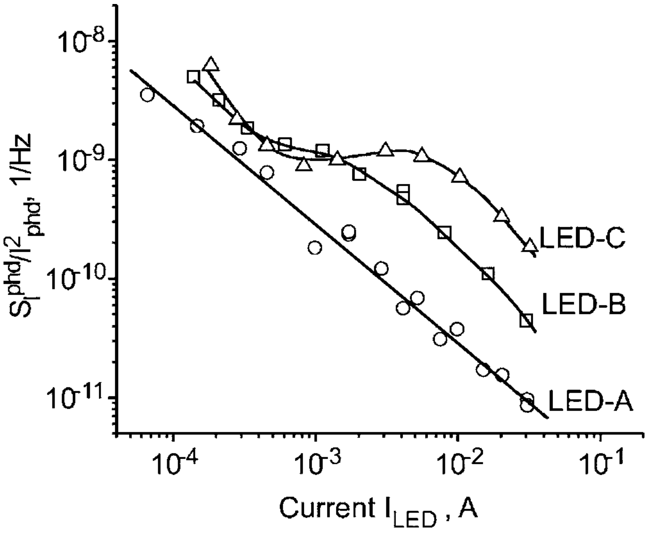

FIG. 1. Dependence of the relative spectral noise density of light intensity fluctuations for LED-A, -B, and -C as a function of current on a log scale. The frequency of analysis is $f=1$ Hz.

The relative spectral noise density of the light intensity fluctuations as a function of the wavelength is shown in Fig. 4 (left-hand axis) for LED-C for two current levels. The data for LED-C for two current levels are also shown in Fig. 4. The corresponding emission spectra are also shown (dashed lines, right-hand axis). The appearance of several maxima in the spectra is attributed to thickness interference fringes in the thin sample. The spectral noise data are given with individual error bars indicating both the accuracy of the noise measurement and the optical bandwidth of the monochromator. Full drawn lines are guides to the eye. In the wings of the emission peak, the noise measurement has larger error

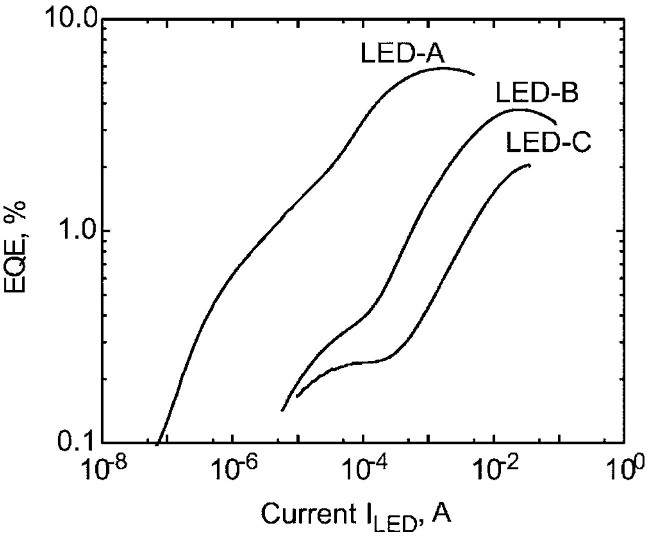

FIG. 2. External quantum efficiency (EQE) of the LEDs as a function of current on a log scale.

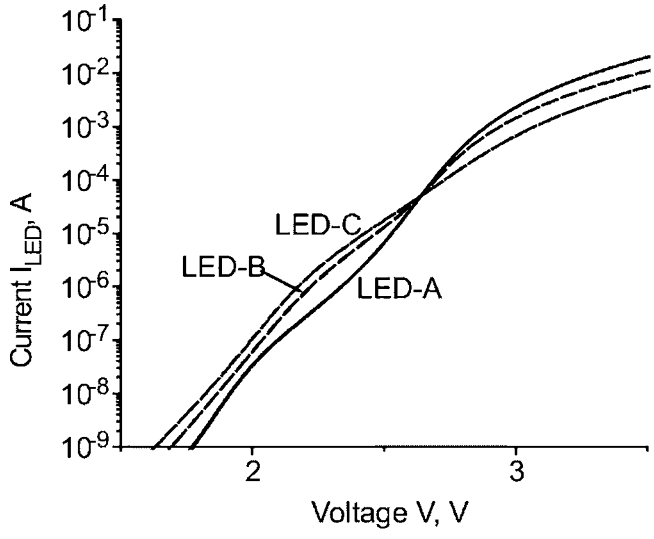

FIG. 3. Current-voltage characteristics of the LEDs.

bars due to the lower light intensity. It is apparent that the light noise decreases as the detection window is swept across the emission peak towards longer wavelengths. This behavior is similar in all LEDs investigated here.

The directly measured total light noise can be compared with the wavelength-resolved noise measurements. The integration 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,

$$\frac{S_I^{\mathrm{phd}}}{I_{\mathrm{phd}}^2} = \frac{\int_{\lambda_1}^{\lambda_2} dS_\lambda^{\mathrm{phd}}}{\left(\int_{\lambda_1}^{\lambda_2} dI_\lambda\right)^2}, \tag{1}$$

or fully correlated,

$$\frac{S_I^{\mathrm{phd}}}{I_{\mathrm{phd}}^2} = \frac{\left(\int_{\lambda_1}^{\lambda_2} \sqrt{dS_\lambda^{\mathrm{phd}}}\right)^2}{\left(\int_{\lambda_1}^{\lambda_2} dI_\lambda\right)^2}, \tag{2}$$

where $dS_\lambda^{\mathrm{phd}}$ and dI_λ are the spectral noise density of the photodiode current fluctuations and the photodiode current for the measurements at some particular wavelength.

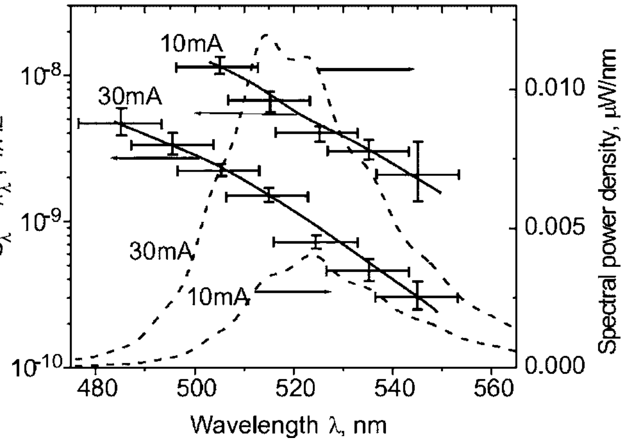

FIG. 4. Relative spectral noise density of the light intensity fluctuations as function of the wavelength within the LED spectral line for the LED-C (solid lines and error bars). The emission spectra of the LED are also shown (dashed lined) as a reference. The frequency of analysis is $f=1$ Hz.

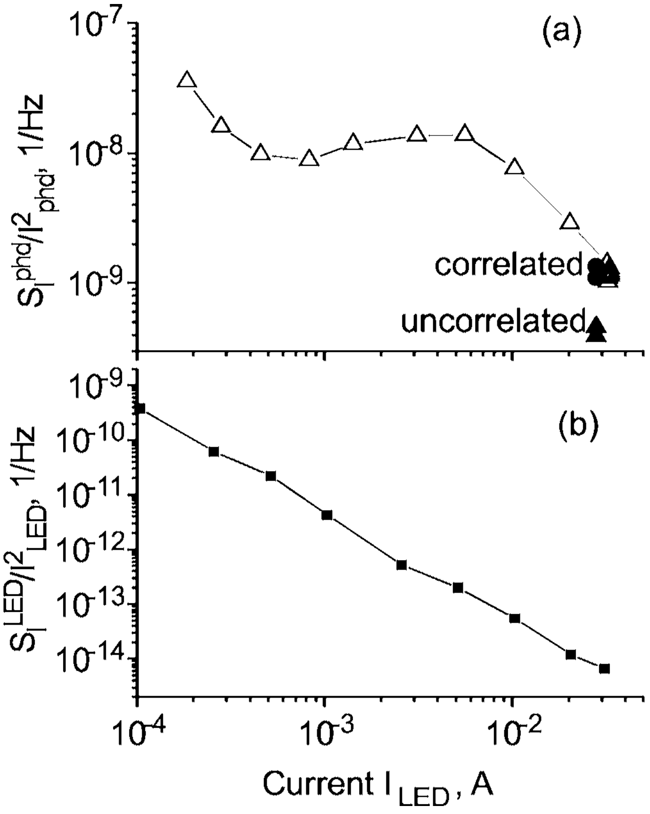

FIG. 5. (a) Relative spectral noise density of light intensity fluctuations as a function of the current for the LED-C. The open symbols show the light intensity noise when the entire LED spectrum is included in the noise measurements. The filled symbols are the integrals obtained from the measurements at different wavelengths assuming correlated (circles) and uncorrelated (triangles) fluctuations. The filled symbols are shifted left for clarity. (b) Current dependence of the relative spectral noise density of the LED current noise $S_I^{\mathrm{LED}}/I_{\mathrm{LED}}^2$.

As seen from the Fig. 5(a), the integral taken, assuming correlation at different wavelengths, fits the experimental results much better than the uncorrelated integration. Apparently, some mechanism must exist that synchronizes the light intensity fluctuations across the very wide width of emission wavelength.

Figure 5(b) shows the relative spectral noise density of the LED current noise $S_I^{\mathrm{LED}}/I_{\mathrm{LED}}^2$ (note that these are not short circuit but actual current fluctuations in the LED circuit with load resistor $R_{\mathrm{LED}}=1$ kΩ). 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.

This correlation and the dependence of noise on the wavelength shown can be explained as follows. 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. (The theoretical limit for the FWHM determined by the thermal distribution of carriers is $1.8kT_c$, where T_c is the effective carrier temperature.[3]) As shown in Ref. 18, additional line broadening in LEDs might come from a nonhomogeneous 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. The fluctuation of carriers concentration spread within the quantum well during the characteristic time of the order d/v_F, where d is the diameter of the LED and v_F is the electron velocity at the Fermi level. This time is much shorter than $1/2\pi f$ (f is the frequency of noise measurements). This can explain why the noise at different wavelengths is correlated. The fluctuation of carriers' concentration affect much stronger the states at the Fermi level than the states well below the Fermi level. Radiative transitions from the Fermi level contribute to the short wavelengths and transitions from states below the Fermi level are responsible for the longer wavelengths. Therefore, noise at shorter wavelength is higher than that at longer wavelength.

IV. CONCLUSIONS

The optical, i.e., light intensity, low-frequency noise was 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 the quantum efficiency and the higher the recombination current. That observation allowed us to conclude that the optical noise is linked to the nonradiative 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 increase with the wavelength decrease. Fluctuations at different wavelengths are found to be correlated. This is thought to be a result of the fast spreading of carriers along the quantum wells.

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[1] I. Akasaki, Mater. Res. Soc. Symp. Proc. **482**, 1 (1998).
[2] S. Nakamura and G. Fasol, *The Blue Laser Diode* (Springer, Berlin, 1997).
[3] A. Zukauskas, M. S. Shur, and R. Gaska, *Introduction to Solid State Lighting* (Wiley, New York, 2002).
[4] C. Wetzel and T. Detchprohm, MRS Internet J. Nitride Semicond. Res. **10**, 2 (2005).
[5] R. J. Fronen, IEEE J. Quantum Electron. **25**, 1653 (1989).
[6] A. Dandrige and H. F. Taylor, IEEE J. Quantum Electron. **18**, 1738 (1982).
[7] X. Y. Chen, M. J. Deen, and C. X. Peng, J. Appl. Phys. **88**, 6746 (2000).
[8] P. Signoret, G. Belleville, and B. Orsal, Fluct. Noise Lett. **1**, L1 (2001).
[9] L. K. J. Vandamme, P. J. L. Herve, and R. Alabedra, *Proceedings of the 14th International Conference, Noise in Physical Systems and 1/f Fluctuations*, Leuven, Belgium, 1997 (World Scientific, 1997), p. 495.
[10] J. J. Brophy, J. Appl. Phys. **38**, 2465 (1967).
[11] S. L. Rumyantsev, M. S. Shur, Yu. Bilenko, P. V. Kosterin, and B. M. Salzberg, J. Appl. Phys. **96**, 966 (2004).
[12] S. L. Rumyantsev *et al.*, J. Appl. Phys. **97**, 123107 (2005).
[13] S. Sawyer *et al.*, J. Appl. Phys. **100**, 034504 (2006).
[14] P. J. L. Herve, L. K. J. Vandamme E, and P. W. M. Blom, *Proceedings of the 14th International Conference, Noise in Physical Systems and 1/f Fluctuations*, Leuven, Belgium, 1997 (World Scientific, 1997), p. 508.
[15] D. Ursutiu and B. K. Jones, Semicond. Sci. Technol. **11**, 1133 (1996).
[16] M. Sampietro, G. Ferrari, D. Natali, U. Scherf, K. O. Annan, F. P. Wenzl, and G. Leising, Appl. Phys. Lett. **78**, 3262 (2001).
[17] C. Wetzel, T. Salagaj, T. Detchprohm, P. Li, and J. S. Nelson, Appl. Phys. Lett. **85**, 866 (2004).
[18] K. Kazlauskas *et al.*, Appl. Phys. Lett. **83**, 3722 (2003).