

Current and optical noise of GaN/AlGaIn light emitting diodes

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Low frequency noise of current and light intensity of ultraviolet light emitting diodes (LED) with wavelength from 265 to 340 nm are the superposition of the $1/f$ and generation-recombination noise. The dependence of generation-recombination noise on the LED current has a maximum caused by a relatively shallow trap level in the quantum well. The upper bound of this trap level concentration is estimated to be $N_t = 7 \times 10^{15} \text{ cm}^{-3}$. The relative spectral noise density of the light intensity fluctuations decreased with an increase of the LED forward current. At high currents, the difference in the noise level for LEDs with different wavelength is small and is of the same order of magnitude or even smaller than for visible LEDs. © 2006 American Institute of Physics. [DOI: 10.1063/1.2204355]

I. INTRODUCTION

Ultraviolet (UV) GaN/AlGaIn light emitting diodes (LEDs) are finding applications in solid-state lighting, medical diagnostics and treatment, water and air purification, chemical- and biological-agent detection, biological fluorescence experiments, and short range communication. For many applications, the light intensity noise is crucial to the overall system sensitivity and performance. This includes identifying miniscule amounts of hazardous biological and chemical agents, and detection of fluorescence from protein molecules excited by the UV light.¹⁻⁴

Investigation of the fluctuations of the LED current (current noise) is an effective tool to study the device quality, reliability, and the degradation processes.⁵⁻⁸ In many cases, low frequency noise in semiconductors is a superposition of the $1/f$ and generation-recombination (GR) noise. While the $1/f$ noise is an indicator of the overall quality of the material or device,^{9,10} GR noise carries information on local levels.¹¹⁻¹⁵

Recently, we reported on the noise characteristics of deep UV LEDs fabricated by Sensor Electronic Technology, Inc. (SET).¹⁶ In this paper, we report on the low frequency current and light intensity noise of the next generation LEDs (also fabricated by SET, Inc.) with wavelengths ranging from 265 to 340 nm. A migration enhanced metalorganic chemical vapor deposition (MEMOCVD[®]) used to grow AlN buffer layer and AlN/AlGaIn superlattice layers and improved optical, electrical, and thermal design (UVTOP[®]) resulted in much better UV LEDs with the wall plug efficiency approaching 1% and power 2.5 mW at dc forward current 20 mA (for 280 nm LEDs).¹⁷

II. EXPERIMENTAL DETAILS

The second generation UV LED structures (SET UVTOP[®] LEDs) were grown in a custom-designed vertical metalorganic chemical vapor deposition (MOCVD) system, with trimethyl aluminum (TMA), trimethyl gallium (TMG), silane, Cp2-Mg, and NH₃ as precursors on basal plane sapphire substrates. In the second generation LEDs, the AlN buffer and superlattices for strain management were grown by MEMOCVD[®]. The active region consisted of five periods of Si-doped quantum wells with the barrier and well thickness at approximately 70 and 35 Å, respectively. The first generation LEDs were also studied for comparison.

The spectral line half width in all second generation LEDs with the wavelength of 265–340 nm did not exceed 11 nm and wall-plug-efficiency for the best devices approached 1% for the dc current $I = 20$ mA. The radiant flux ranged from 0.2 to 2.5 mW depending on the wavelength for LEDs of $2 \times 10^{-4} \text{ cm}^2$ active area.

The LED light intensity fluctuations were measured by a UV enhanced Si photodiode UV-100L from UDT Sensors, Inc. biased by a low noise battery using a load resistor, $R_{\text{phd}} = 10 \text{ k}\Omega$. In order to eliminate the contribution of the LED series resistance to the light intensity fluctuations¹⁶ the LED load resistor was taken to be $R_{\text{LED}} = 1 \text{ k}\Omega$. The experimental setup is shown in Fig. 1.

For the current noise measurements, the LED load resistor varied from 100 Ω to 10 k Ω , depending on the LED current. The short circuit current fluctuations were calculated as $S_1 = S_v (R_{\text{LED}} + R_d)^2 / (R_{\text{LED}} R_d)^2$ (where R_d is the LED differential resistance).

The voltage fluctuations S_v across the resistors R_{phd} and R_{LED} were amplified by a signal recovery low noise amplifier (model 5184) and analyzed using a SR 770 Network Analyzer (see Fig. 1).

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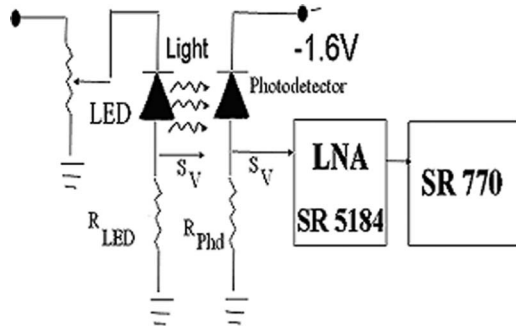


FIG. 1. Scheme of the experimental setup.

III. CURRENT FLUCTUATIONS

For the majority of the second generation LEDs, the noise spectra of current fluctuations at low currents ($I_{LED} < 10^{-4}$ A) were superposition of the $1/f$ and GR noise (see Fig. 2). At high currents the noise spectra were very close to the $1/f$ noise for most devices. For the first generation LEDs, the $1/f$ noise dominated at all currents. No random telegraph noise was found in contrast to finding of Ref. 8.

For some devices, the GR noise was distinguishable for the entire range of the measured currents. Figure 3 shows the $S_I \times f$ versus frequency f dependences for one of the 280 nm SET UVTOP® LEDs for currents from 1.2×10^{-6} to 3.2×10^{-3} A. (The dependences are shifted vertically for clarity.) As seen, at least two GR processes (A and B) contribute to the noise.

Figure 4(a) shows the current dependence of noise at frequency $f=10$ Hz, for several LEDs. For the first generation LED, this dependence is similar to that of a typical $p-n$ junction. At low currents, the slope of the dependence is close to the $S_I \propto I_{LED}$ law, manifesting the main contribution to the noise originating from the barrier resistance. The

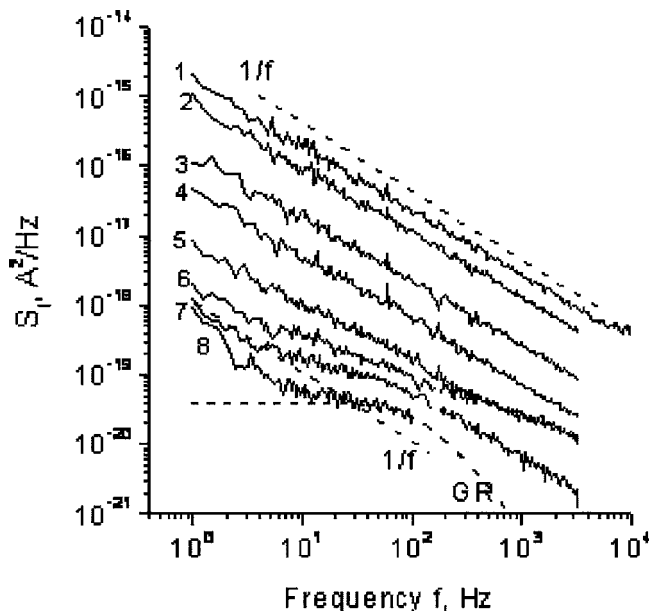


FIG. 2. Noise spectra S_I of the second generation SET UVTOP® 280 nm LED (LED R2) for different currents: 1– 5×10^{-3} A, 2– 3×10^{-3} A, 3– 10^{-3} A, 4– 5×10^{-4} A, 5– 1.7×10^{-4} A, 6– 8.3×10^{-7} A, 7– 3.1×10^{-7} A, and 8– 1.3×10^{-7} A. Dashed lines are guides for the eye.

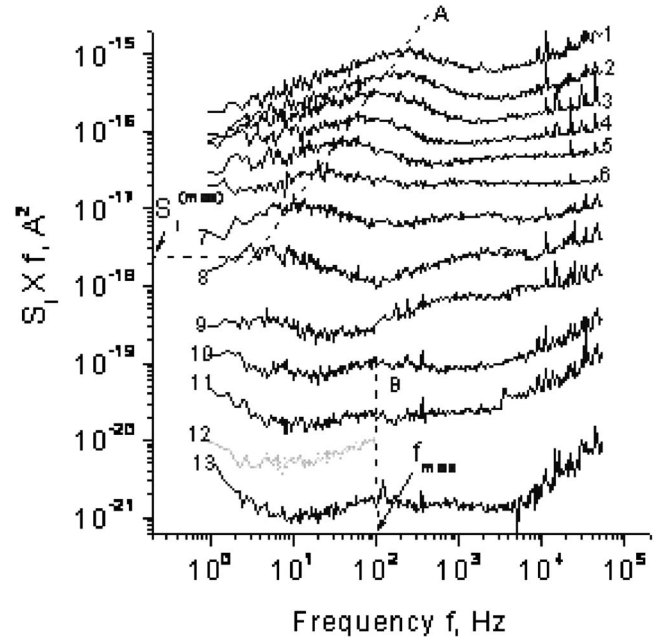


FIG. 3. Noise spectra times frequency $S_I \times f$ for the second generation SET UVTOP® 280 nm LED (LED S4) for different currents: 1– 3.2×10^{-3} A, 2– 2.2×10^{-3} A, 3– 6.9×10^{-4} A, 4– 1.7×10^{-4} A, 5– 4×10^{-5} A, 6– 2×10^{-5} A, 7– 10^{-5} A, 8– 9.7×10^{-6} A, 9– 6.5×10^{-6} A, 10– 4.8×10^{-6} A, 11– 3.3×10^{-6} A, 12– 1.9×10^{-6} A, and 13– 1.2×10^{-6} A. The line 1 is an original dependence; all others are shifted down 3 dB relatively to the neighbor one for the clarity.

physical mechanism of $S_I \propto I_{LED}$ law is not clear yet, however; this kind of dependence for the forward biased $p-n$ junction was observed in multiple publications (see Ref. 18 for the references and discussion). At high current $S_I \propto I_{LED}^2$, which is characteristic for the noise from the diode series resistance.

The second generation LEDs demonstrate completely different behavior. At small current $I_{LED} < 10^{-5} - 10^{-6}$ A, the spectral noise density S_I increases with the current increase. For intermediate current levels, $10^{-4} - 10^{-3}$ A $> I_{LED} > 10^{-5} - 10^{-6}$ A, the spectral noise density S_I either decreases with or depends weakly on the current. At higher currents, $S_I \propto I_{LED}^2$. For these high currents (at current $I_{LED} > 10^{-3}$ A), the noise of the second generation LEDs is always smaller than that for the first generation devices, manifesting a suppressed contribution to noise from the series resistance (base and/or contact noise).

As seen from Fig. 4(a), at small currents, the current dependence of noise for some of the LEDs has a maximum. To the best of our knowledge, such dependence has never been reported before for a $p-n$ junction. This type of the noise current dependence is typical for the range of currents, where GR noise dominates.

In most cases, GR noise was observed at low biases, where the total resistance was dominated by the barrier resistance. Therefore, we can assume that GR noise also originated from the $p-n$ barrier and not from the adjoining p and n layers or contacts. The GR noise due to the recombination current in $p-n$ junction was analyzed in several publications (see Refs. 19 and 20 and references therein). These papers analyzed the noise associated with recombination current determined by a single recombination level.

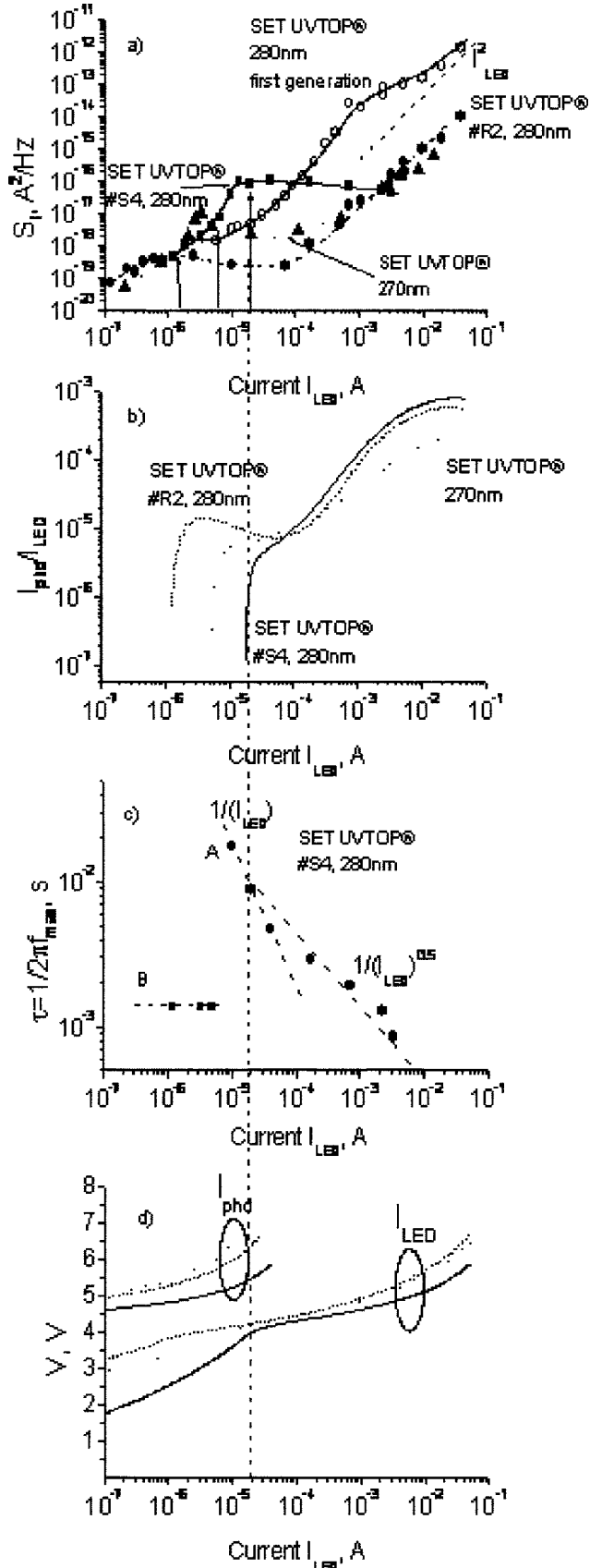


FIG. 4. Dependences of the noise spectral density S_I at $f=10$ Hz (a), I_{phd}/I_{LED} (b), and characteristic time $\tau=1/2\pi f_{max}$ (c) (see Fig. 2 for the definition of f_{max}) on the LED current. (d) shows the voltage-current characteristics. Vertical arrows in (a) show the light emission threshold current. Solid, dashed, and dot lines in (a), (b), and (d) correspond to the same devices.

Another possible noise mechanism involves a trap level located relatively close to one of the bands. This trap enables the exchange of carriers with this band (the conduction band for electrons or the valence band for holes). Let us assume that the level responsible for the capture and emission of electrons is closer to the conduction band. The occupancy of this trap level and electron concentration in the quantum well fluctuate, and the spectral noise density of concentration fluctuations in this case is given by:¹¹⁻¹³

$$\frac{S_n}{n^2} = \frac{4N_t \tau F(1-F)}{Vn^2 [1 + (\omega\tau)^2]}, \quad (1)$$

where N_t is the trap concentration, n is the electron concentration in the quantum well, τ is the characteristic time of the GR noise, V is the volume, and F is the occupancy of the level. The characteristic time τ can be expressed as $\tau = \tau_c F$, where $\tau_c = (\sigma n v)^{-1}$ is the capture time, σ is the capture cross section, v is the thermal velocity.²¹ For the nondegenerate case the position of quasi-Fermi level is given by $E_F = kT \ln(N_c/n)$. Then the level occupancy can be expressed as

$$F = \frac{1}{1 + (N_c/n) e^{-E_t/kT}}, \quad (2)$$

where N_c is the effective density of states in the conduction band and E_t is the level position (the energy is measured down from the bottom of the conduction band).

We now consider two limiting cases for low frequencies $\omega\tau \ll 1$.

A. Low currents (monomolecular recombination)

In this case, the current is proportional to the electron concentration,

$$I_{LED} = \frac{qnV}{\tau_r}, \quad (3)$$

where τ_r is the recombination time, which does not depend on the concentration of the injected carriers, n .

At low currents, the electron concentration n is small and the trap level is almost empty ($F \ll 1$). Then the spectral noise density of current fluctuations S_I for $\omega\tau \ll 1$ can be expressed as

$$S_I = \frac{q^2 V^2}{\tau_r^2} S_n = \frac{4N_t q I_{LED}}{\tau_r \sigma v N_c^2} e^{2E_t/kT} \propto I_{LED}. \quad (4)$$

As seen, the noise S_I increases with the current increase.

With a further current increase, the occupancy of the trap level also increases. Assuming that $(1-F) \ll 1$ and that the recombination is still monomolecular, we obtain

$$S_I = \frac{q^4 V^3}{\tau_r^4} \frac{4N_t N_c e^{-E_t/kT}}{\sigma v I_{LED}^2} \propto \frac{1}{I_{LED}^2}. \quad (5)$$

As seen, in this case, noise S_I decreases with the current increase. A maximum on the noise current dependence corresponds to the level occupancy $F=2/3$. For $\omega\tau_c F=1$, this maximum is

$$S_I^{\max} = \frac{4q^2VN_f\tau}{9\tau_r^2}, \quad (6)$$

where $\tau = \tau_c F = 1/2\pi f_{\max}$ (see Fig. 3). Equation (6) allows us to estimate the concentration N_f . Taking for the estimate the lifetime in GaN $\tau_r = 2 \times 10^{-9}$ s (Ref. 22) for the LED with the highest GR noise [LED S4 (see Fig. 4(a))] we obtained $N_f = 7 \times 10^{15}$ cm $^{-3}$.

B. High current (bimolecular recombination)

A still further current increase leads to the radiative (bimolecular) recombination and generation of the light. In this case, the current and the current spectral noise density S_I can be expressed as

$$I_{\text{LED}} = n^2 B q V / \eta \quad (7)$$

$$S_I = 4IBqVS_n/\eta,$$

where B is radiative recombination coefficient and η is the internal quantum efficiency. Combining (1) and (7) for the case $(1-F) \ll 1$, we obtain that the spectral noise density is independent of the current,

$$S_I = 16B^2 q^2 V \frac{N_f N_c e^{-E_f/kT}}{\sigma \eta^2 \nu} \quad (8)$$

As follows from Eqs. (4), (5), and (8), experimental dependences of noise versus current can be qualitatively described as follows: at low currents, the noise first increases with the current increase, then reaches a maximum and then decreases when the level occupancy exceeds $F=2/3$. At higher currents, the radiative bimolecular recombination contributes to the current. As shown above, if radiative recombination dominates, S_I does not depend on current. The internal quantum efficiency is always less than unity and depends on current. Therefore, several (at least two) recombination mechanisms contribute to the current for high currents. Combination of monomolecular and bimolecular processes give either flat or decreasing dependence of S_I on current in agreement with the experimental data [see Fig. 4(a)].

Figure 4(b) shows the dependence of $I_{\text{phd}}/I_{\text{LED}}$ (which is proportional to the external quantum efficiency) for the same second generation LEDs as in Fig. 4(a). It is seen that there is a threshold for the light generation which varies from 10^{-6} to 10^{-5} A for different devices. Vertical arrows in Fig. 4(a) show the threshold current for the second generation LEDs. One can see that, in the agreement with the above estimates, decrease or flattening of the noise dependences on current corresponds to the currents higher than the threshold current.

Another proof that flat or decreasing part of noise current dependence corresponds to the bimolecular recombination comes from Fig. 4(c) which shows the dependence on the GR characteristic time $\tau = 1/2\pi f_{\max}$ on current for two GR processes (where f_{\max} is frequency corresponding to the maximum on the $S_I \times f$ vs f dependence [see Fig. 3]). For high currents, $\tau = \tau_c F \approx \tau_c \approx (\sigma \nu n)^{-1}$. Since for the bimolecular recombination, $n \sim I^{0.5}$, the characteristic time, τ , should

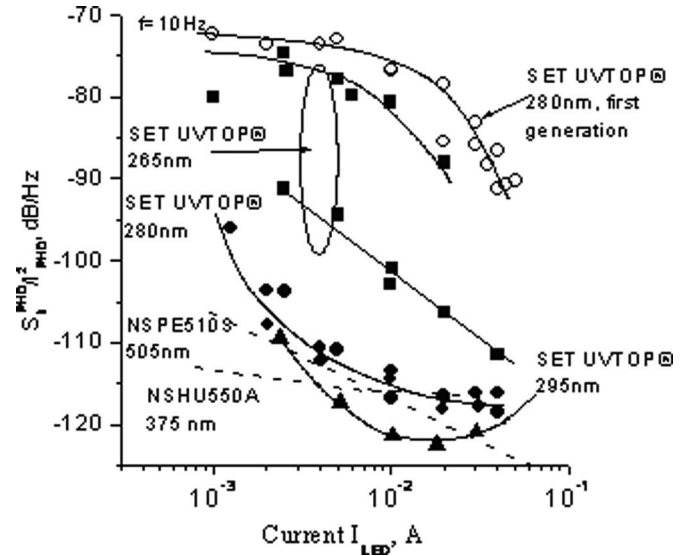


FIG. 5. Dependence of relative noise spectra $S_I^{\text{phd}}/I_{\text{phd}}^2$ on LED current, I_{LED} , for different LEDs. Frequency of analysis $f=10$ Hz. Dashed lines show the noise level for NICHIA NSHU550A (375 nm) and NICHIA NSPE5105 (505 nm).

depend on current as $\tau \sim I^{0.5}$. For lower currents when monomolecular recombination dominates, characteristic time τ should depend on current as $\tau \sim I^1$. As seen from the Fig. 4(c) For the GR process, A, the current dependence of the time τ changes from $\tau \sim I^1$ to $\tau \sim I^{-0.5}$ as it should. The transition current roughly corresponds to the threshold of the light generation [Fig. 4(b)] and to the maximum on the noise versus current dependence shown in Fig. 4(a). The same transition current corresponds to the knee on the voltage-current characteristic [Fig. 4(d)].

At very low currents, the occupancy function F might be less than unity for the given trap level ($E_F - E_i$). If $F \ll 1$, characteristic time $\tau = (\sigma \nu N_c)^{-1} \exp(E_i/kT)$ does not depend on concentration and current. As seen from the Fig. 3 and Fig. 4(c) that is the case for the GR process B. That allows us to estimate the trap position responsible for the GR noise B. Taking for the estimate the lifetime in GaN $\tau_r = 2 \times 10^{-9}$ s (Ref. 22) we found $E_F = 0.19$ eV for $I = 5 \times 10^{-5}$ A. Therefore the level with $E_i < 0.19$ eV is responsible for the GR noise B.

IV. LIGHT INTENSITY FLUCTUATIONS

At low frequencies $f < 1$ kHz, the $1/f^\gamma$ spectra of the light intensity fluctuations with $\gamma = 1-1.4$ was dominant for all UV LEDs. At higher frequencies, the shot noise or the thermal noise of load resistor R_{phd} were dominant.

Figure 5 shows $S_I^{\text{phd}}/I_{\text{phd}}^2$ at frequency $f=10$ Hz as a function of the LED current for several LEDs under study. For comparison, the dashed lines show the noise level for the commercially available Nichia LEDs with 505 and 375 nm wavelengths. As seen, the relative spectral noise density of the light intensity fluctuations decreases with the increase of the LED current.

At high currents, the difference in the noise level for LEDs with different wavelengths is small, with the exception for the shortest wavelength (265 nm LEDs), which demonstrated high dispersion of the noise level from device to de-

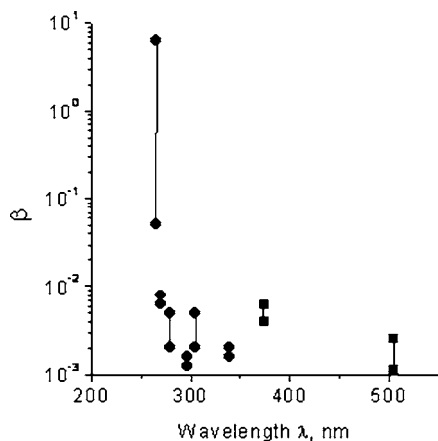


FIG. 6. Quality factor β as function of the LED wavelength for the second generation SET UVTOP® LEDs (circles), Nichia LEDs NSHU550A and NICHIA NSPE510S (squares)

vice. Open symbols show the noise level for the first generation 280 nm LEDs, which is more than two orders of magnitude higher than for the recent devices. The SET UVTOP® LEDs (second generation) demonstrated the noise level of the same order of magnitude or smaller as the longer wavelength LEDs (NICHIA NSHU550A and NICHIA NSPE510S.)

Figure 6 shows the LED noise quality factor $\beta = (S_I/I_{\text{phd}}^2)fn(\tau/q)I_{\text{LED}}$, where n is the number of chips connected in series ($n=1$ for all LEDs studied in this paper), τ is the radiation lifetime, q is the electronic charge.²³ As seen, all LEDs demonstrate the quality factor β of the same order of magnitude, with exception of the shortest 265 nm LEDs.

V. CONCLUSIONS

The second generation SET UVTOP® LEDs with the AlN buffer and superlattices grown by the migration enhanced MOCVD demonstrate optical and current noise, which is substantially smaller than for the first generation LEDs. This result is achieved due to the reduction of the noise from series base resistance. For the second generation SET UVTOP® LEDs, the noise spectra of the current fluctuations are the superposition of the $1/f$ and GR noise. This GR noise demonstrated unusual nonmonotonic dependence on the current, which is explained by the presence of a relatively shallow trap levels in the quantum well. The trap level

concentration responsible for this GR noise is estimated to be $N_t=7 \times 10^{15} \text{ cm}^{-3}$. For the shallowest trap level trap B the estimate of the level position yields $E_t < 0.19 \text{ eV}$.

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