Investigation of Efficiency Droop for UV-LED with N-type AlGaN Layer

Po-Min Tu *[a], Jet-Rung Chang[b], Shih-Cheng Huang[a], Shun-Kuei Yang[a], Ya-wen Lin[a],
Tzu-Chien Hung[a], Chih-Peng Hsu[a], and Chun-Yen Chang[b]

[a] Advanced Optoelectronic Technology Inc., Hsinchu 30352, Taiwan.
[b] Department of Electronic Engineering, National Chiao Tung University, 1001 Ta Hsueh Rd.,
Hsinchu 300, Taiwan.

ABSTRACT

The efficiency droop in InGaN-based 380nm UV light emitting device (LED) with n-GaN and n-AlGaN underlayer grown on sapphire substrate by metal-organic chemical vapor deposition (MOCVD) was investigated. From simulation result of high resolution x-ray diffraction (HRXRD) ω-2θ curve by using dynamical diffraction theory, the Al composition in the n-AlGaN layer was determined to be about 3%. The experimental results of temperature dependent photoluminescence (PL) demonstrated that the internal quantum efficiency (IQE) of n-GaN and n-AlGaN UV-LEDs are 43% and 39%, respectively, which are corresponding to an injected carrier density of 8.5×10^{17} #/cm^3. It could be explained that the crystal quality of n-GaN is better than of n-AlGaN. In addition, the observation of pit density from atomic force microscopy (AFM) surface morphology is consistent with the interpretation. It was well-known that the pits appearing on the surface in the virtue of the threading dislocations. Thus, it means that defects induce the non-radiative centers and deteriorate the IQE of the UV-LED with n-AlGaN underlayer. Therefore, the light output power of n-GaN UV-LED is slightly higher below the forward current of 250 mA. Nevertheless, the output power was enhanced about 22% as the injection current was increased to 600 mA. Furthermore, the external quantum efficiency (EQE) of n-AlGaN UV-LED was nearly retained at the 600 mA (only 20% droop), whereas the UV-LED with n-GaN exhibits as high as 33%. We attributed this improvement to the less self-absoption by replacing n-GaN underlayer with n-AlGaN.

Keywords: GaN, UV-LEDs, Droop.

1. INTRODUCTION

Recently, the GaN-based ultraviolet light emitting diodes (UV-LEDs) have been focused on as one of the most important targets for the pumping source to develop white-light LEDs. However, it is difficult to fabricate near-UV LEDs with high efficiency, because the external quantum efficiency (EQE) decreases drastically below the wavelength of 400 nm [1]. This is due to the smaller InN mole fluctuation with reduced indium composition in the near-UV quantum wells (QWs), and thus less localized energy states lead to lower efficiency of the near-UV LEDs [2, 3]. Moreover, crystalline quality and light absorption of GaN are significant for short wavelength near-UV LEDs [4, 5]. Besides, most of the light will be trapped inside the GaN-based LED, resulting in the low light extraction efficiency [6]. Once the light trapped inside, the LED will be reabsorbed eventually. On the other hand, the junction temperature, the temperature of the active region, is a critical parameter and affects quantum efficiency of device, maximum output power, reliability, and other parameters. In general, heat can be generated in the ohmic contact, cladding layers, and the non-radiative recombination in the active region [7]. In this study, we proposed to remove the conventional n-type GaN below InGaN multi-quantum-wells (MQWs) and replaced it with an n-type $Al_{0.03}Ga_{0.97}N$ to improve the optical performance in the UV GaN LEDs.

* bomin.tu@aot.com.tw; phone 886-3-597-6988 ext. 16872; fax 886-3-597-1700.

2. EXPERIMENT

The samples in this study were grown on c-plane 2" sapphire substrates by using an atmospheric-pressure metal organic chemical vapor deposition (AP-MOCVD SR4000) system. The metalorganic compounds of trimethylgallium, trimethylaluminum, trimethylindium and ammonia (NH3) were employed as the reactant source ma-terials for Ga, Al, In, and N, respectively. Silane and bis-cyclopentadienyl magnesium (Cp$_2$Mg) were used as the sources for n-type and p-type dopants, respectively. Prior to the growth, the sapphire substrates were thermal cleaned in hydrogen ambient at 1100°C. As shown in Fig.1, the UV LED structure with InGaN/AlGaN multi-quantum-well (MQW) consisted of a 30-nm-thick low-temperature (500°C) GaN nucleation layer (GaN NL), a 2-μm-thick undoped GaN epilayer (u-GaN), a 2-μm-thick Si-doped n-layer, an InGaN/AlGaN multiple quantum wells (MQWs) active layer, a 15-nm-thick Mg-doped AlGaN electron blocking layer (p-AlGaN) and a 0.2-μm-thick Mg-doped GaN contact layer (p-GaN). In this study, Si-doped GaN and Si-doped Al$_{0.03}$Ga$_{0.97}$N n-type layer were grown and denoted as UV-LED with n-GaN and UV-LED with n-AlGaN, respectively. Temperature dependent photoluminescence (PL) and Power-dependent PL were used to determine internal quantum efficiency (IQE) and internal electric field (IEF), respectively. In addition, these samples were also characterized by atomic force microscopy (AFM) to reveal the surface morphology. Electrical and optical characteristics were measured by electroluminescence (EL). Their junction temperatures were extracted from the current–voltage (*I–V*) curves measured under DC current condition for a broad temperature range, from 30 °C to 130 °C. Finally, the UV LED wafers were processed into mesa-type chips (size: 1mm×1mm) and mounted on epoxy-free metal can (TO-39). The output power of the LED chips was measured using an integrated sphere detector.
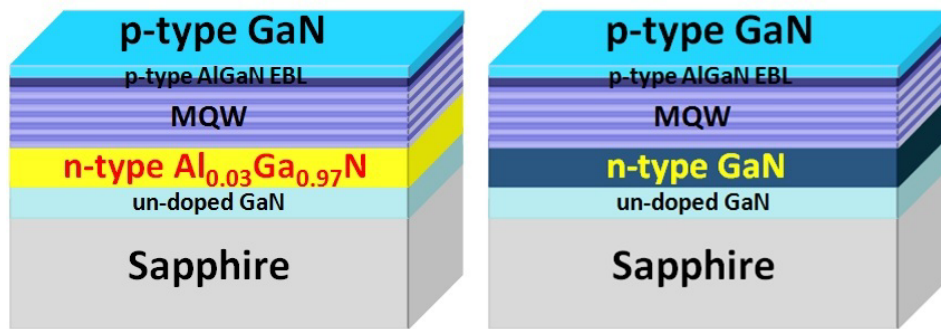

Figure 1. Schematic illustrations of GaN UV-LEDs with n-AlGaN and n-GaN.

3. RESULT AND DISCUSSION

Firstly, the surface morphologies of UV-LEDs with n-AlGaN and n-GaN were investigated by AFM, as shown in Fig. 2.(a) and (b). The root mean square (rms.) value of the UV-LEDs with n-AlGaN and n-GaN were 1.36 nm and 0.60 nm, respectively. While, it can be clearly seen that, the pit density of the UV-LEDs with n-AlGaN and n-GaN were 6.5×10^9 cm^{-2} and 4×10^9 cm^{-2}, respectively. It have been reported that the pits appearing on the surface correspond to the threading dislocations. Fig. 2 (c) and (d) shows the dependence of the IQE of UV-LED with n-GaN and UV-LED with n-AlGaN as a function of injected carrier density at 15K and 300K. As the excitation energy increases, the IQE of UV-LED with n-GaN is usually higher than UV-LED with n-AlGaN at 300K. The experimental results demonstrated that the IQE are 43% and 39%, respectively, which are corresponding to an injected carrier density of 8.5×10^{17} #/cm^3 [8]. It could be explained by the crystal quality of n-GaN is better than that of n-AlGaN. In addition, the observation of pit density of AFM morphology is consistent with the interpretation. It was well-known that the pits appearing on the surface in the virtue of the threading dislocations. Thus, it means that defect-induced non-radiative centers deteriorated IQE of LED with n-AlGaN layer. Therefore, it can be believed that the crystalline quality of the UV-LED with n-GaN is slightly better than the UV-LED with n-AlGaN.
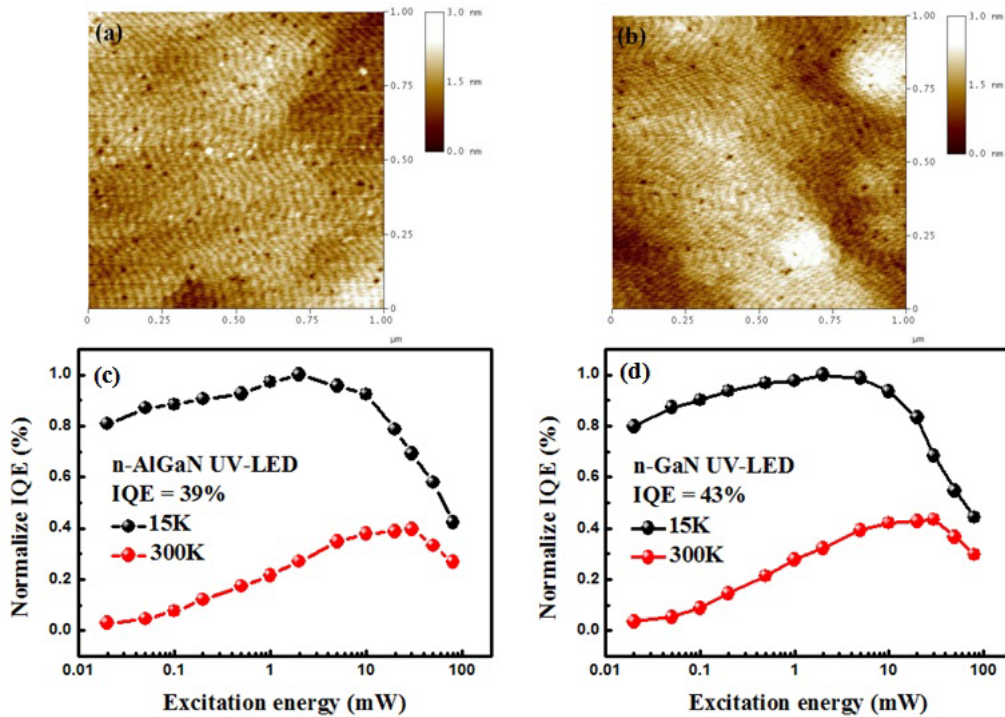
Figure 2. AFM analysis over 1x1 μm^2 for (a) UV-LED with n-AlGaN (b) UV-LED with n-GaN. The IQE of UV-LEDs with (c) n-AlGaN and (d) n-GaN as a function of excitation power at 15K and 300 K.

Fig. 3(a) shows the injection current versus voltage (I-V) characteristics of the both LEDs. Under a forward current of 350 mA, the forward voltage was 3.92 and 4.07 V for UV-LED with n-GaN and UV-LED with n-AlGaN. A little high forward voltage of UV-LED with n-AlGaN can be attributed to the higher Al content compare to the UV-LED with n-GaN, thus increase the series resistance in the device. The (I-V) characteristics of both are almost the same. The light output power versus injection current (L–I) characteristics of both UV-LEDs are also shown in Fig. 3(b). The light output powers are 60mW and 63mW with the injection current at 350 mA for UV-LEDs with n-GaN and n-AlGaN, respectively. The light output powers are quite similar for both LEDs at 350 mA. However, when the injection current is increased to 600 mA, the output power of UV-LED with n-AlGaN has is much better than UV-LED with n-GaN. The light output powers for UV-LEDs with n-GaN and n-AlGaN are 70 mW and 86 mW, individually. There exhibits 22% enhancement in UV-LED with n-AlGaN compared to UV-LED with n-GaN at 600mA. This indicates that UV-LED with n-AlGaN had higher efficiency at high injection current. Fig. 3(c) shows the normalized efficiency curves as a function of forward current for the two samples. The UV LED with n-GaN attain to the normalized efficiency maximize with the forward current at 200mA and begin to decrease. On the other hand, the UV LED with n-AlGaN attain to the normalized efficiency maximize with the forward current at 250mA and keep the normalized efficiency maximize to the forward current at 350 mA then start to decrease. From AFM and IQE measurements, it revealed that the crystal quality of the UV-LED with n-GaN is slightly better than UV-LED with n-AlGaN. Therefore, the light output power of UV-LED with n-GaN was slightly higher below 250 mA. For the UV LED with n-GaN, when the injection current exceeds 600mA, the efficiency is reduced to 33% of its maximum value. In contrast, the UV LED with n-AlGaN exhibit only 20% efficiency droop when increasing the injection current to 600 mA. These results indicate that the UV LED with n-AlGaN not only enhance the total light output power but successfully improve the efficiency at high injection current. In general, the ideal semiconductor has a zero band-to-band absorption coefficient at the bandgap energy (E=Eg). However, the absorption strength in the real semiconductor, for below-bandgap light, can be expressed in terms of exponentially decaying absorption strength. The absorption coefficient, α of the $Al_{0.03}Ga_{0.97}N$ and GaN films are 8×10^2 and 1.2×10^3 cm^{-1} at 380nm, respectively [9]. The transmission percentage of AlGaN and GaN are 85% and 77%, respectively. The light absorbing magnitude of GaN is 8% more than AlGaN at 380nm, which is significantly related to the peak shift result. In other ward, the droop effect issue has been improved in ultraviolet LEDs.
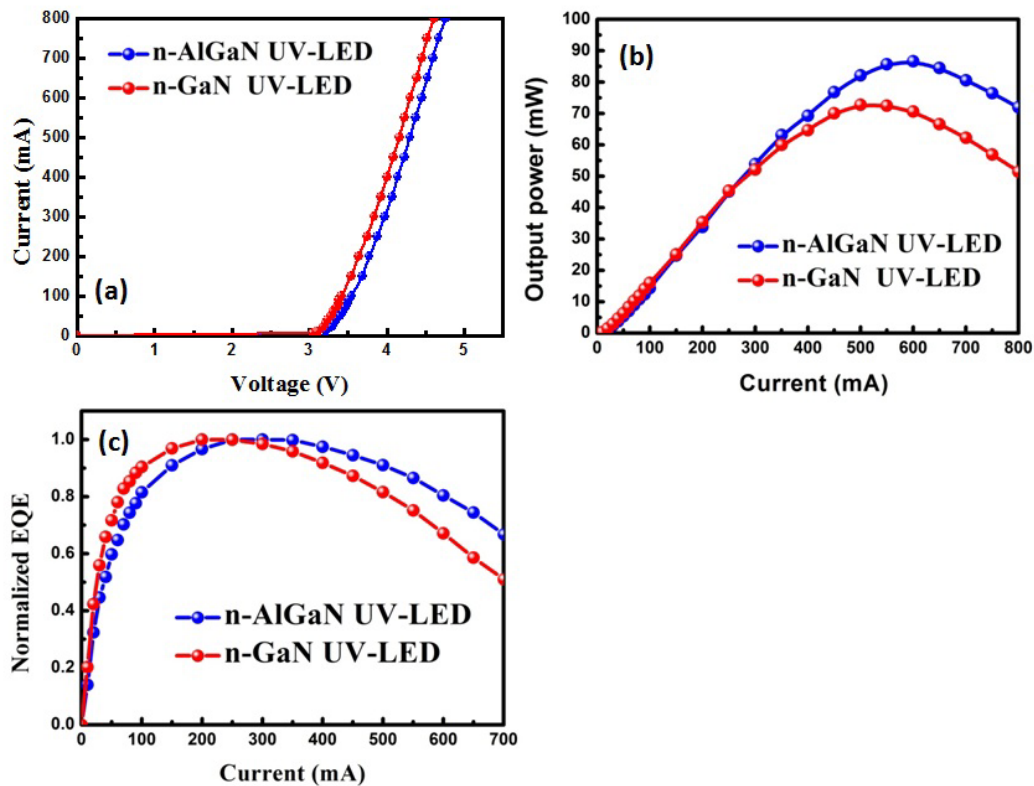
Figure 3. (a) Injection current versus voltage and (b) the light output power versus injection current characteristics for UV-LED with n-AlGaN and UV-LED with n-GaN (c) Normalized EQE curve for UV-LED with n-AlGaN and UV-LED with n-GaN.

Fig. 4 shows the emission peak energy under different excitation power. It was found that the peak of the emission spectra of the LEDs shift to higher energy when the excitation power increased. The blue shift of both UV-LEDs with increasing excitation power may be explained by the carrier screening of the QCSE resulting from piezoelectric fields. In addition, the IEF was fitted by the peak energy shift under various injection levels at RT [10]. Our result shows the IEF of the both UV-LEDs was 0.198 MV/cm. Therefore, it was clarified that, in this case, QCSE is not the main reason to influence the characteristic of the light output power and efficiency droop.
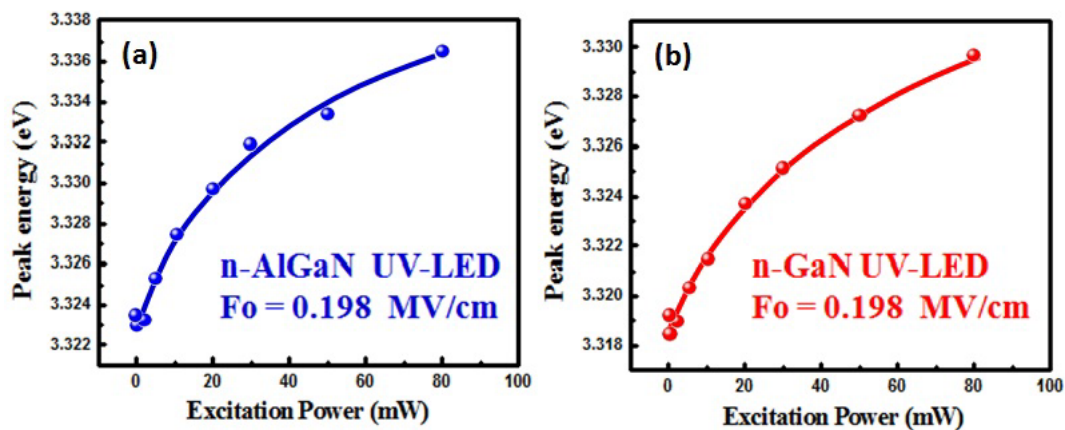

Figure 4. Emission energy of UV-LED with (a) n-AlGaN and (b) n-GaN at different power density.

Fig. 5(a) depicts the variation of the emission peak versus injection current characteristics of these UV-LEDs. It was shown that the initial peak positions of both UV-LEDs were located at about 380 nm, and the appearance of monotonic red-shift was revealed with increasing current. It was recognized that the junction temperature increased as the injection current increased. The red-shift magnitudes of UV LEDs with n-GaN and n-AlGaN were 6.6 and 4.3nm, respectively. This implied that the phenomenon of red-shift is more serious in UV LED with n-GaN. Moreover, the full width at half maximum (FWHM) of both UV-LEDs increased with increasing current as shown in Fig. 5(b), and the FWHM variations of UV LEDs with n-GaN and n-AlGaN were 3.5 nm and 2.6 nm, respectively. In our experiment, the difference between each sample is mainly in the Al mole fraction in the n-type layer. In previous results, no matter in crystalline quality, piezoelectric field and IQE, there are no immensely distinction between UV-LEDs with n-AlGaN and n-GaN. However, from EL spectrum peak shift result, the different self-heating phenomena of UV-LEDs have been observed [11]. Therefore, we suggested that the heat is generated from the absorption of light in the n-type layer, leading to the broadening of FWHM and red-shift. As a matter of fact, the self-absorption of emitting light in LEDs will generate heat, which means the performance of LEDs will deteriorate. Fortunately, the larger band gap of $Al_{0.03}Ga_{0.97}N$ can significantly suppress the self-absorption effect in LEDs. Thus, these results indicated that the self-heating phenomenon of UV LED with n-GaN is much serious than UV LED with n-AlGaN.
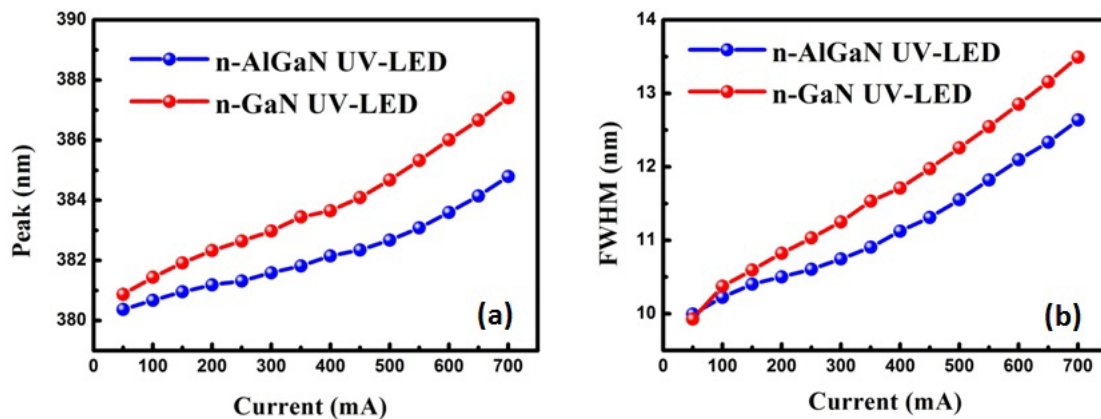

Figure 5. EL characteristics of (a) peak shift and (b) FWHM versus injection current for UV-LEDs with n-GaN and n-AlGaN.

Fig. 6 shows the junction temperature versus injection current characteristics of both UV-LEDs. The junction temperature of the UV-LED with n-GaN is always higher than UV-LED with n-AlGaN. Also, it can be clearly seen that the ΔT increases as increasing the injection current. The observation was consistent with EL analyses, which showed that the existence of temperature difference between n-type $Al_{0.03}Ga_{0.97}N$ and GaN. Consequently, self-heating effect will occur and lead to a quantum efficiency droop. As well-known, a semiconductor material absorbs photon energy when the photon energy is larger than the band-gap energy, wheasc the semiconductor material is transparent when photon energy is smaller than the band-gap energy [9]. By Urbach tail law, a semiconductor material also can absorb below band-gap light even though the absorption coefficient is small. From energy point of view, the absorbed light transfers to thermal energy will influence on the performance of LED device.
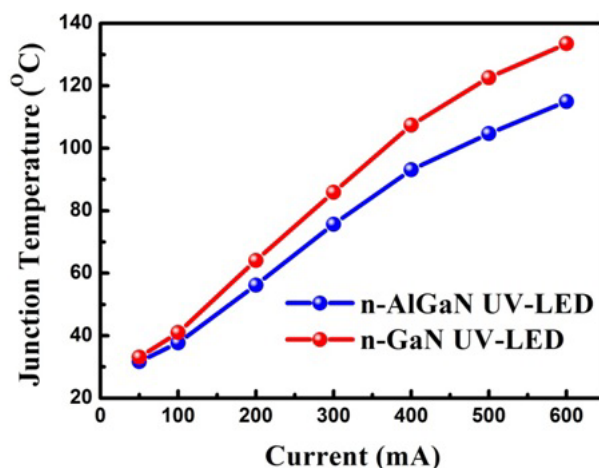
Figure 6. The junction temperature as a function of injection current of UV-LEDs with n-AlGaN and n-GaN.

4. CONCLUSION

The quantum efficiency droop in InGaN-based 380nm UV LED with n-GaN and n-Al$_{0.03}$Ga$_{0.97}$N underlayer grown on sapphire substrate by metal-organic chemical vapor deposition (MOCVD) was investigated. The measurements of temperature dependent PL and AFM revealed that the crystal quality of UV-LED with n-GaN is slightly better than that with n-AlGaN. Nevertheless, the output power of n-AlGaN UV-LED was enhanced from 70 mW to 86 mW (about 22%) as the injection current was increased to 600 mA. The n-AlGaN UV-LED exhibits only 20% quantum efficiency droop and 22% power enhancement at high injection current, we attributed this improvement can be less self-absoption by replacing n-GaN nuderlayer with n-AlGaN.

REFERENCES

[1] H. Hirayama, "Quaternary InAlGaN-based high efficiency ultraviolet light-emitting diodes," J. Appl. Phys. **97**, 091101-091119 (2005).
[2] I. H. Ho and G. B. Stringfellow, "Solid phase immiscibility in GaInN," Appl. Phys. Lett. **69,** 2701-2703 (1996).
[3] T. Mukai and S. Nakamura, "Ultraviolet InGaN and GaN Single-Quantum-Well-Structure Light-Emitting Diodes Grown on Epitaxially Laterally Overgrown GaN Substrates." Jpn. J. Appl. Phys. **38**, 5735-5739 (1999).
[4] R. H. Horng, W. K. Wang, S. C. Huang, S. Y. Huang, S. H. Lin, C. F. Lin, and D. S. Wuu, "Growth and characterization of 380-nm InGaN/AlGaN LEDs grown on patterned sapphire substrates," J. Cryst. Growth **298,** 219-222 (2007).
[5] D. Morita, M. Yamamoto, K. Akaishi, K. Matoba, K. Yasutomo, Y. Kasai, M. Sano, S. i. Nagahama and T. Mukai, "Watt-Class High-Output-Power 365 nm Ultraviolet Light-Emitting Diodes," Jpn. J. Appl. Phys. **43**, 5945-5950 (2004).
[6] T. Fujii, Y. Gao, R. Sharma, E. L. Hu, S. P. DenBaars, and S. Nakamura, "Increase in the extraction efficiency of GaN-based light-emitting diodes via surface roughening," Appl. Phys. Lett. **84**, 855-857 (2004)
[7] K. C. Yung, H. Liem, H. S. Choy, and W. K. Lun, "Degradation mechanism beyond device self-heating in high power light-emitting diodes," J. Appl. Phys **109,** 094509-094514 (2011).
[8] Y. J. Lee, C. H. Chiu, C. C. Ke, P. C. Lin, T. C. Lu, H. C. Kuo, and S. C. Wang, "Study of the Excitation Power Dependent Internal Quantum Efficiency in InGaN/GaN LEDs Grown on Patterned Sapphire Substrate," IEEE Journal of Selected Topics in Quantum Electronics **15,** 1137-1143 (2009).

[9] D. Brunner, H. Angerer, E. Bustarret, F. Freudenberg, R. Hopler, R. Dimitrov, O. Ambacher, and M. Stutzmann, "Optical constants of epitaxial AlGaN films and their temperature dependence," J. Appl. Phys. **82,** 5090-5096 (1997).

[10] A. Chtanov, T. Baars, and M. Gal, "Excitation-intensity-dependent photoluminescence in semiconductor quantum wells due to internal electric fields," Phys. Rev. B **53,** 4704-4707 (1996).

[11] Y. Yang, X. A. Cao, and C. Yan, "Investigation of the Nonthermal Mechanism of Efficiency Rolloff in InGaN Light-Emitting Diodes, " IEEE Trans Electron Devices **55,** 1771-1775 (2008).