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Fabrication and Characterization of a GaN Light-emitting Diode (LED) with a Centered Island Cathode

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Uniform spreading of injection current in light-emitting diodes (LEDs) is one of the crucial requirements for better device performances. It is reported that non-uniform current spreading leads to low output power, high current crowding, heating, and reliability degradation of the LED device. This paper reports on the effects of different surface and electrode geometries in the LEDs. To increase the output power of LEDs and reduce the series resistance, a rectangular-type LED (RT-LED) with a centered island cathode has been fabricated and investigated by comparison with a conventional LED (CV-LED). The performances of RT-LEDs were prominently enhanced via uniform current spreading and low current crowding. Performances in terms of increased output power and lower forward voltage of simulated RT-LEDs are much superior to those of CV-LEDs. Based on these results, we investigated the correlation between device geometries and optical characteristics through the fabricated CV and RT-LEDs. The measured output power and forward voltage of the RT-LEDs at 100 mA are 64.7% higher and 8% smaller compared with those of the CV-LEDs.

Keywords : Light-emitting diode, Electrode geometries, Centered island cathode, Output power
OCIS codes : (080.2740) Geometric optical design; (160.4670) Optical materials; (220.4610) Optical fabrication; (230.3670) Light-emitting diodes; (350.4600) Optical engineering

I. INTRODUCTION

GaN-based LEDs have been widely developed in many electronic industries related to full color displays, automobile lights, and other visible and non-visible lights due to a number of advantages such as low power consumption, long duration lifetime, and ecological-friendliness [1-6]. Although the LED technology has been remarkably evolved, there are still issues to be resolved for enhancing device performances, such as high joule heating and low light emission efficiency. Output power of LEDs is affected strongly by the wall-plug efficiency (η_{total}) that is determined from the product of internal efficiency (η_{int}), electrical efficiency (η_{elec}), and extraction efficiency (η_{ext}). η_{int}, mainly related with the material quality, is enhanced by low-defect epitaxial growth and optimized multiple quantum wells (MQWs). η_{elec} is improved by better ohmic contact and higher electron mobility. η_{ext}, more related with device geometry and surface /interface quality of the LED, can be enhanced by physical approaches including reduction of total internal reflection (TIR), patterning the substrate, giving textures to p-GaN anode, and novel device structures [7-9]. Conventional LEDs (CV-LEDs) generally are composed of asymmetric sturcture (in the radial direction), which results in low optical efficiency due to the high current crowding effect occurring at a certain localized active region between n- and p-electrodes [10-11].

In this paper, the optical performance of a rectangular type LED (RT-LED) with a centered island cathode is demonstrated by fabrication results and supporting simulation data. The optical and electrical characteristics of the RT-LED are enhanced by the reduction of current crowding near the n-electrode by the structural symmetries of the n- and p-electrodes [12]. Also, the identical current path between cathode and anode makes injection current uniform over

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the whole device. Therefore, η_{elec} increases as the effective area where electron-hole recombinations take place is enlarged by the help of uniform current injection. In addition to the optical and electrical performances, the device temperature of the RT-LED at the forward bias operation is dramatically reduced compared with that of CV-LED. Thus, heating-induced reliability degration is also substantially reduced.

II. DEVICE FABRICATION

Figure 1(a) shows the schematic diagram of RT-LED for a GaN-based 460-nm blue LED. The epitaxial multi-layers were grown on the patterned sapphire substrate by using metal-organic chemical vapor deposition (MOCVD). It consists of a GaN buffer layer for the epitaxy process, un-doped GaN layer, Si-doped n-GaN layer, InGaN/GaN multiple quantum wells, and Mg-doped p-GaN layer. The thicknesses of n- and p-type GaN layers were 4 μm and 300 nm, respectively, and the doping concentrations were Si 3×10^{18} cm^{-3} and Mg 6×10^{17} cm^{-3}. The exact atom fractions in InGaN in the quantum wells were 23% In and 77% Ga ($In_{0.23}Ga_{0.77}N$). Each pair was composed of 3-nm $In_{0.23}Ga_{0.77}N$ and 10-nm GaN, which made up a 65-nm quantum-well region by employing 5 pairs. As the transparent metallic layer for effective current spreading, a Ni (50 Å)/Au (50 Å) multi-layer was deposited on a p-GaN layer and then annealed by a rapid thermal process (RTP) at 500℃ in the N_2/O_2 ambient to form stable ohmic contacts [13-14]. A Ti (300 Å)/Au (4000 Å) multi-layer for electrode metal was deposited by an electron beam (e-beam) evaporator. The n-type electrode was formed on the mesa etched n-GaN layer at the center of the LED as show in Fig. 1(b) and a p-type electrode was formed on the p-GaN layer with rectangular ring type. The CV- and RT-LED devices were fabricated on the same chip and went through the same process conditions. Also, the areas of p-GaN layer (1.62×10^5 μm^2), current spreading layer (1.39×10^5 μm^2) and electrodes (10^4 μm^2) of the RT-LED were designed to be the same as those of the CV-LED.

In designing an LED device, it is essential to extract the current spreading length from the material and process conditions and to utilize it as a design rule [15-16]. The distance between p- and n-electrodes of the RT-LED was also determined to be shorter than the current spreading length at the material conditions that we employed. The current spreading length is mathematically induced as follows [16]:

$$\text{(Current spreading length)} = \sqrt{(\rho_c + \rho_p t_p)\left|\frac{\rho_n}{t_n} - \frac{\rho_1}{t_1}\right|^{-1}}.$$

Here, ρ_c is the contact resistance between the transparent layer and the p-type GaN layer. $\rho_{p/n}$, and $t_{p/n}$ are the resistivity and thickness of the p/n-GaN layer, respectively. In the similar fashion, ρ_t, and t_t are those of the transparent layer. For a well-made GaN Led, the contact resistance is known to be in the 10^{-3}-$\Omega\cdot cm^2$ order [17], and we assumed that $\rho_c = 5\times10^{-3}$ $\Omega\cdot cm^2$ for our work. ρ_p of Mg-doped p-type GaN (ρ_p) at Mg 6×10^{17} cm^{-3} is around 2 $\Omega\cdot cm$

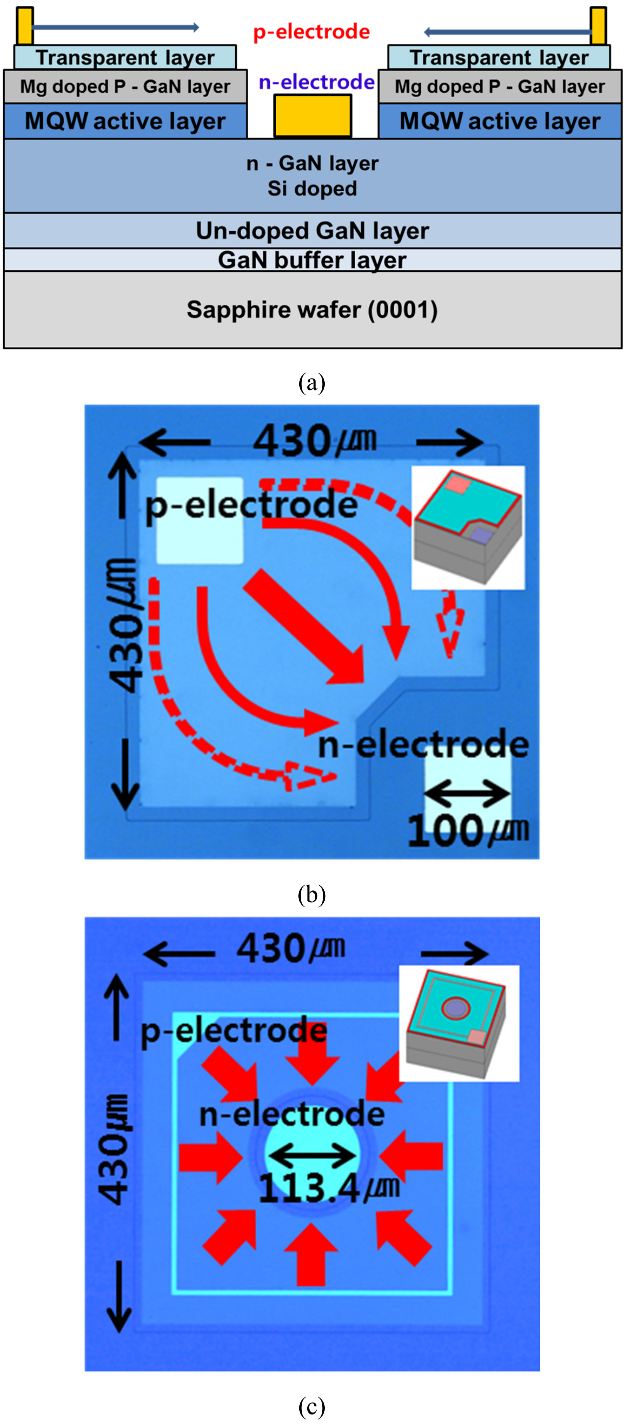
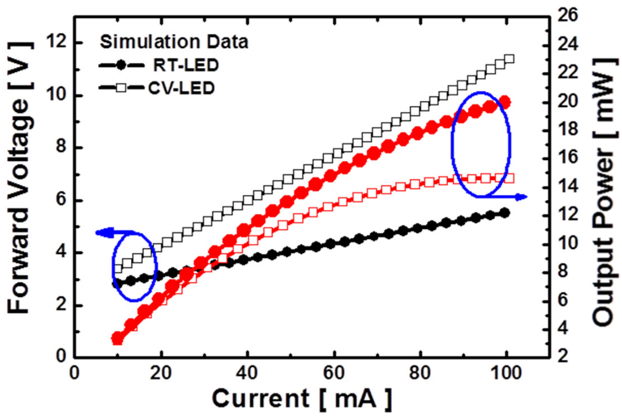


FIG. 1. Schematic views of the fabricated LEDs. (a) Cross-sectional view of RT-LED. Top views of (b) CV-LED and (c) RT-LED.

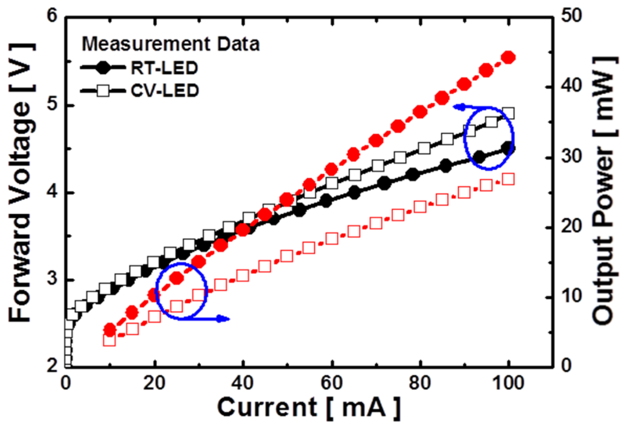
[18], and t_p = 0.3×10^{-4} cm as given above. ρ_n of Si-doped n-type GaN at Si 3×10^{18} cm^{-3} is around 0.03 Ω·cm [19], and t_n was given as 4×10^{-4} cm. Ni and Au thicknesses were commonly 50 Å. ρ_t/t_t = 25 Ω for the Ni/Au film with a 1:1 thickness ratio when the film thickness is 100 Å in our case, according to the experimental data [16]. Substituting these values into the equation gives the current spreading length of 100.6 μm. The distance between the n-type island electrode and the surrounding p-type electrode is 93 μm and that between bonding pad is 98.6 μm, which confirms that the designed RT-LED meets the design rule with current spreading length.

III. RESULTS AND DISCUSSIONS

Prior to the LED fabrication, we investigated the performances of CV- and RT-LED by an optical simulation tool, SpeCLED [20]. Fig. 2(a) shows the simulated current -voltage (*I-V*) and optical output power characteristics of the CV- and RT-LED. The total p-electrode metal areas of CV- and RT-LED devices in Figs. 1(b) and (c) were made



(a)

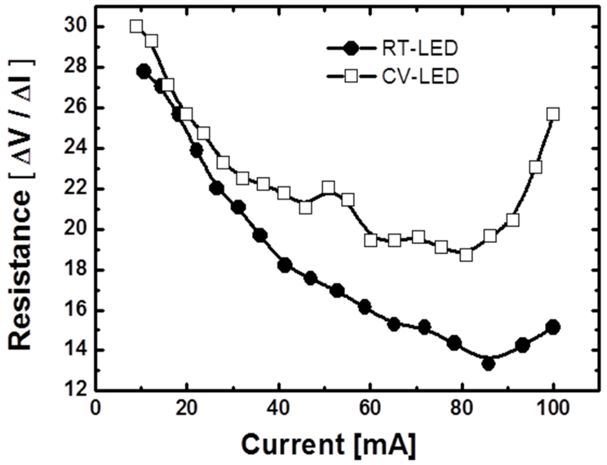


(b)

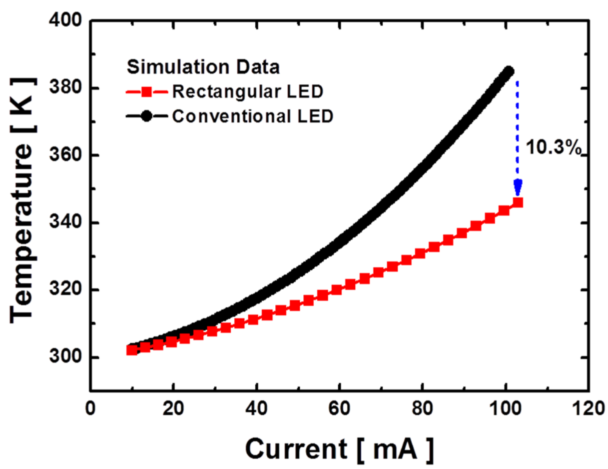
FIG. 2. Current-voltage characteristics and output power of CV- and RT-LED. (a) Simulation and (b) Measurement results.

the same, which, in consequence, reduced the actual area of p-electrode bonding pad (the left upper area where probing in the measurements is made). By this design approach, we could make the areas covered by the metals as well as the areas of active regions the same in both devices to make fair comparisons. Additional simulations revealed that local changing the p-pad area of RT-LED has little effect on current drivability. As shown in Fig. 2(a), the RT-LED shows higher optical power and necessitates lower forward operation voltage at all current levels than the CV-LED. Based on the simulation results, we investigated the performances of the fabricated RT-LED compared with those of the CV-LED. Fig. 2(b) shows the measured *I-V* characteristic of CV-LED and RT-LED under the forward operation voltage. The measurements were performed by direct probing the p- and n-electrodes labeled in Figs. 1(b) and (c). In Fig. 2(b), the current reflects the total current injected into the diode when voltage is applied between anode and cathode of the LED. At an injection current of 100 mA, the forward voltage of the RT-LED (4.5 V) is lower than that of the CV-LED (4.9 V). It indicates that the power consumption of the RT-LED is substantially lower than that of the CV-LED at the identical injection current. Although CV- and RT-LEDs have the same surface areas, the p- and n-type electrodes are asymmetrically located in the device and most current flows along the shortest path, in the diagonal direction, from p- to n-type electrode. In this case, current crowding effect takes place near each electrode, which increases series resistance and self-heating. On the other hand, electrical characteristic of the RT-LED is enhanced by uniform current spreading and shorter distance between two electrodes. Fig. 2(b) shows the optical output power of CV- and RT-LEDs as a function of current applied to the LED. Output power of the RT-LED when the applied currents for measurement are 20 mA and 100 mA is more improved by about 43.5% and 64.7% as compared with those of CV-LED, respectively. The light emitting efficiency of the CV-LED is dominated by the diagonal current path due to the non-uniform current spreading and the light extraction along the edge is negligibly small. However, in the case of the RT-LED, the n-type electrode is surrounded by the p-type electrode in all directions. Thus, the current spreads more uniformly on the surface, and thus, electron-hole radiative recombinations are increased.

In order to confirm the directional uniformity of the injected currents, we observed the series resistance of fabricated LEDs. Fig. 3(a) shows the series resistance of CV- and RT-LEDs obtained by differentiations (*dV*/*dI*) from the I-V curve in Fig. 2(b). As a result, a series resistance at 20-mA current injection is 24 Ω for the RT-LED, which was a little bit lower than that of the CV-LED, 25 Ω. As the current injection increases, series resistances decreases and the difference between those of CV- and RT-LED devices becomes more prominent: at 100-mA current injection, resistances of CV- and RT-LEDs were 26 Ω and 15 Ω, respectively. It is



(a)



(b)

FIG. 3. Resistance and luminescence efficiency of CV- and RT-LED. (a) Resistance as a function of injection current. (b) Simulated average device temperature as a function of injection current.

observed that that more current crowding in the CV-LED leads to higher series resistance due to interruption of current flow in the direction of the perimeter. The increase of series resistance due to non-uniform current also results in a rise in temperature of the LED [21-24]. As shown in the Fig. 3(b), the device temperature of the RT-LED predicted by simulation is about 343 K at 100 mA and it is 10.3% lower than 384 K of the CV-LED. Therefore, the RT-LED is operated with higher reliability in thermal perspective.

Figure 4 shows the luminescence efficiency of the RT-LED and the CV-LED. In this result, the RT-LED demonstrated improved luminescence efficiencies by 61.7% and 106.3% at two different current biases of 20 mA and 100 mA, respectively. The current flow in the RT-LED is distributed in every radial direction with the same distance between p- and n-electrodes, covering the whole device surface and active region. Therefore, the electron-hole recombination extracting the light is drastically enhanced. Also, it is more probable that the light emission from the etched mesa sidewall is observed through both top and sidewall surfaces [3-4]. On the other hand, the local current -crowding in the small volume of region, for the case of the CV-LED, degrades the recombination rate.

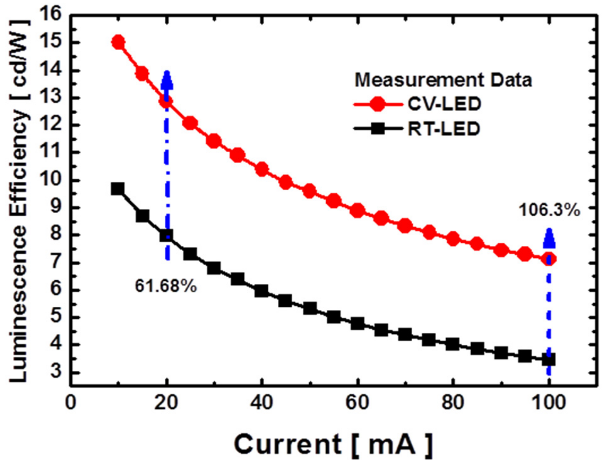


FIG. 4. Measured luminescence efficiency of CV- and RT-LED as a function of injection current (10 mA to 100 mA).

IV. CONCLUSION

In this work, we fabricated and demonstrated CV- and RT-LED devices. For more rigorous characterization of the designed RT-LED and its comparison with the CV-LED, the measurement analyses were accompanied by simulations. The electrode structures of the RT-LED led to uniform current spreading and reduced the series resistance. Through engineering the electrode geometry, RT-LED demonstrated higher electrical and optical performances. For wider commercialization of the RT-LED with centered island electrode, reliability issues such as short circuit-free wiring, degradation of external quantum efficiency, and failure by wire heating should be further studied.

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REFERENCES

1. C. G. Son, J. H. Yi, J. S. Gwag, J. H. Kwon, and G. Park, "Improvement of color and luminance uniformity of the edge-lit backlight using the rgb LEDs," J. Opt. Soc. Korea **15**, 272-277 (2011).
2. H.-Y. Ryu and D.-H. Kim, "High-brightness phosphor-conversion white light source using InGaN blue laser diode," J. Opt. Soc. Korea **14**, 415-419 (2010).
3. S. E. Brinkley, C. L. Keraly, J. Sonoda, C. Weisbuch, J. S. Speck, S. Nakamura, and S. P. DenBaars, "Chip shaping for light extraction enhancement of bulk c-plane light-emitting diodes," Appl. Phys. Express **5**, 032104-1~032104-3 (2012).
4. J.-Y. Kim, M.-K. Kwon, J.-P. Kim, and S.-J. Park, "Enhanced light extraction from triangular GaN-based light-emitting diodes," IEEE Photon. Technol. Lett. **19**, 1865-1867 (2007).
5. C.-M. Yang, D.-S. Kim, S.-G. Lee, J.-H. Lee, Y. S. Lee, and J.-H. Lee, "Improvement in electrical and optical performances of GaN-based LED with SiO_2/Al_2O_3 double dielectric stack layer," IEEE Electron Device Lett. **33**, 564-566 (2012).
6. C. S. Chang, S. J. Chang, Y. K. Su, C. T. Lee, Y. C. Lin, W. C. Lai, S. C. Shei, J. C. Ke, and H. M. Lo, "Nitride-based LEDs with textured side walls," IEEE Photon. Technol. Lett. **16**, 750-752 (2004).
7. M. R. Krames, M. Ochiai-Holcomb, G. E. Hofler, C. Carter-Coman, E. I. Chen, I.-H. Tan, P. Grillot, N. F. Gardner, H. C. Chui, J.-W. Huang, S. A. Stockman, F. A. Kish, and M. G. Craford, "High-power truncated-inverted -pyramid $(Al_xGaN_{1-x})_{0.5}In_{0.5}P/GaP$ light-emitting diodes exhibiting >50% external quantum efficiency," Appl. Phys. Lett. **75**, 2365-2367 (1999).
8. C.-C. Kao, H.-C. Kuo, H.-W. Huang, J.-T. Chu, Y.-C. Peng, Y.-L. Hsieh, C. Y. Luo, S.-C. Wang, C.-C. Yu, and C.-F. Lin, "Light-output enhancement in a nitride-based light-emitting diode with 22° undercut sidewalls," IEEE Photon. Technol. Lett. **17**, 19-21 (2005).
9. P. H. Chen, L. C. Chang, C. H. Tsai, Y. C. Lee, W.-C. Lai, M.-L. Wu, C.-H. Kuo, and J.-K. Sheu, "GaN-based light-emitting diodes with pillar structure around the Mesa region," IEEE J. Quantum Electron. **46**, 1066-1071 (2010).
10. C.-K. Li and Y.-R. Wu, "Study on the current spreading effect and light extrantion enhancement of vertical GaN/ InGaN LEDs," IEEE Trans. Electron Devices **50**, 400-406 (2012).
11. J.-I. Shim, J. Yun, and H. Kim, "Current spreading and its related issues in GaN-based light emitting diodes," Proc. SPIE **7216**, 72160V-1~72160V-9 (2009).
12. S. J. Lee, "Electrode design for InGaN/sapphire LED's based on multiple thin ohmic metal patches," Proc. SPIE **5530**, 338-346 (2004).
13. S. Hwang and J. Shim, "A method for current spreading analysis and electrode pattern design in light-emitting diodes," IEEE Trans. Electron Devices **55**, 1123-1128 (2008).
14. J. O. Song, J.-S. Ha, and T.-Y. Seong, "Ohmic-contact technology for GaN-based light-emitting diodes: role of P-type contact," IEEE Trans. Electron Devices **57**, 42-59 (2010).
15. H. Kim, J. Cho, J. W. Lee, S. Yoon, H. Kim, C. Sone, Y. Park, and T.-Y. Seong, "Consideration of actual current -spreading length of GaN-based light-emitting diodes for high-efficiency design," IEEE J. Quantum Electron. **43**, 625-632 (2007).
16. H. Kim, S.-J. Park, and H. Hwang, "Lateral current transport path, a model for GaN-based light-emitting diodes: applications to practical device designs," Appl. Phys. Lett. **81**, 1326-1328 (2002).
17. X. A. Cao, E. B. Stokes, P. Sandvik, N. Taskar, J. Kretchmer, and D. Walker, "Optimization of current spreading metal layer for GaN/InGaN-based light emitting diodes," Solid -State Electron. **46**, 1235-1239 (2002).
18. M. Lachab, D.-H. Youn, R. S. Qhalid Fareed, T. Wang, and S. Sakai, "Characterization of Mg-doped GaN grown by metal organic chemical vapor deposition," Solid-State Electron. **44**, 1669-1677 (2002).
19. J. R. L. Fernandez, C. M. Araujo, A. F. da Silva, J. R. Leite, B. E. Sernelius, A. Tabata, E. Abramof, V. A. Chitta, C. Persson, R. Ahuja, I. Pepe, D. J. As, T. Frey, D. Schikora, and K. Lischka, "Electrical resistivity and band-gap shift of Si-doped GaN and metal-nonmetal transition in cubic GaN, InN and AlN systems," J. Crst. Growth **231**, 420-427 (2001).
20. STR Group, Online available at http://www.infotc.co.kr.
21. S. C. Bera, R. V. Singh, and V. K. Garg, "Temperature behavior and compensation of light-emitting diode," IEEE Photon. Technol. Lett. **17**, 2286-2288 (2005).
22. Y. Lin, Y.-L. Gao, Y.-J. Lu, L.-H. Zhu, Y. Zhang, and Z. Chen, "Study of temperature sensitive optical parameters and junction temperature determination of light-emitting diodes," Appl. Phys. Lett. **100**, 202108-1~202108-4 (2012).
23. D.-S. Shin, D.-P. Han, J.-Y. Oh, and J.-I. Shim, "Study of droop phenomena in InGaN-based blue and green light-emitting diodes by temperature-dependent electroluminescence," Appl. Phys. Lett. **100**, 153506-1~153506-4 (2012).
24. K. A. Bulashevich, I. Y. Evstratov, V. F. Mymrin, and S. Y. Karpov, "Current spreading and thermal effects in blue LED dice," Phys. Status Solidi C **4**, 45-48 (2007).