Internal quantum efficiency of InGaN/GaN LEDs with short period superlattice and two-colour quantum wells

Ilya E. Titkov*[a], Amit Yadav[a], Modestas Zulonas[a], Vera L. Zerova[a], Andrey F. Tsatsulnikov[b], Wsevolod V. Lundin[b], Alexey V. Sakharov[b], and Edik U. Rafailov[a]
[a]Photonics and Nanoscience Group, School of Engineering, Physics and Mathematics, University of Dundee, Dundee, DD1 4HN, UK;
[b]Ioffe Physico-Technical Institute, Russian Academy of Sciences, Politekhnicheskaya str. 26, 194021 St. Petersburg, Russia

ABSTRACT

Internal Quantum Efficiency (IQE) of blue, deep green and two-colour monolithic white LEDs were measured by temperature dependant electro-luminescence (TDEL) and analysed with modified rate equation based on ABC model. External, internal and injection efficiencies of blue and green quantum wells were analysed separately. All the investigated structures are based on a combination of the short-period superlattice and InGaN quantum well (QW) layers. Monolithic white LEDs contained one green InGaN QW and two blue QWs being separated by GaN barrier. This paper reports also the tuneable behaviour of CCT in pulsed operation mode and effect of self-heating on device performance.

Keywords: internal quantum efficiency, short-period superlattice, monolithic white LED, tuneable CCT

I. INTRODUCTION

Nowadays the most of white LEDs are made using a phosphor coating that converts emissions from InGaN/GaN blue LED to yellow. The best reported devices have maximum external quantum efficiency (EQE) of 85% at the emission wavelength of 440 nm and luminous efficacy of 250 lm/W obtained by the blue light conversion with a mixture of appropriate phosphors.[1] Usual commercially available blue LEDs have EQE about 40% at operation current (350mA) and luminous efficacy of about 160 lm/W. This hybrid approach brings in disadvantages of unavoidable Stokes loss[2,3] (about 20%) occurring in phosphor and addition of fabrication step in the device process.

Monolithic white LEDs based on InGaN/GaN MQWs has being developed already for over 10 years[4,5,6]. To achieve phosphor-free white light emission various approaches were used: different shape and size nanostructures[7,8]; QW light converter[6]; dichroic filter[9], DBR resonant-cavity[10] etc. A monolithic approach of two or three quantum wells emitting at different wavelengths can be also used to generate white light. To see the way through and meet the goals of efficiency and colour parameters there is a need of innovation and optimization at each level of device technology from material growth to packaging. External quantum efficiency (EQE) of such monolithic devices still needs improvement.

New approach to monolithic white LED was recently suggested by A. F. Tsatsulnikov et. al[11,12]. The authors first used short-period superlattice (SPSL) to improve free carriers injection between blue and green QWs, but maximal EQE was less than 10%. The paper[11] claimed there are two reasons for the poor efficiency of the monolithic white LEDs: the low internal quantum efficiency and non-uniform carrier injection into various QWs. Nevertheless, direct investigation of IQE or injection efficiencies (IE) in such structures has never been reported before. This paper is targeted to complete this study with more details and at extended operation currents and also reports the tuneable behaviour of correlated colour temperature (CCT) in pulse operation mode at extremely high currents up to 2A.

Samples

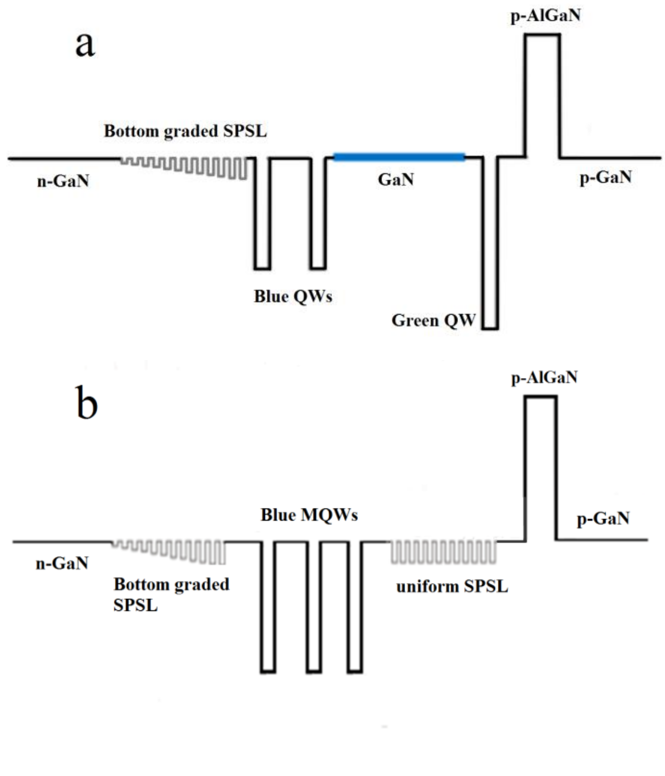
Three different structures were under study: white LED that is similar to the structure used before[11] just without SPSL in the barrier between blue and green QWs (Fig 1a); blue LED with two SPSLs in claddings (Fig. 1b) and green LED with one SPSL in n-cladding layer (Fig. 1c).

All the three types of LED sample were grown by MOCVD on c-plane sapphire substrate with an underlying GaN buffer layer which supports the n-GaN layer of 10^{18} cm^{-3} Si-doping concentration. On top of this n-GaN layer a bottom graded SPSL in grown. For blue and two colours LED structure the graded SPSL thickness is 24 nm with an alternate 1 nm deposition InGaN and GaN making a 12 period SPSL of InGaN/GaN. These SPSLs were grown by conversion method described by W.V. Lundin et. al[13]. For green LED structure this SPSL was replaced by 3 periods of InGaN(7 nm)/GaN(1 nm) grown is same manner with a thickness of 24 nm. On top of SPSL all the three structures support a 12 nm i-GaN barrier layer before the deposition of QW's.

The blue LED structure has three InGaN QW's of 3 nm thickness separated by 8 nm i-GaN and is followed by 8 nm i-GaN barrier layer. This barrier layer if followed by a 12 period SPSL of InGaN/GaN similar to the bottom graded SPSL.

For two colour LED structure the bottom graded SPSL with i-GaN barrier layer supports two InGaN QW's with band gap energy corresponding to blue wavelength of the visible spectrum and a single InGaN QW with energy gap corresponding to green wavelengths of the spectrum. All the three QW's are spatially 8 nm apart from each other with i-GaN used to have that separation in space. The top green QW in two colour LED and top blue QW in blue LED is followed by 8 nm i-GaN barrier layer, 18 nm AlGaN EBL layer and 180 nm p-GaN layer.

For the green structure, the 3 period InGaN/GaN with on top barrier i-GaN layer is followed by a single 3 nm InGaN QW with energy gap corresponding to green emission. The QW is confined in energy space by 8 nm thick i-GaN barrier layer. On top of this 18nm AlGaN EBL layer is grown which in turn supports the 180 nm p-GaN layer.



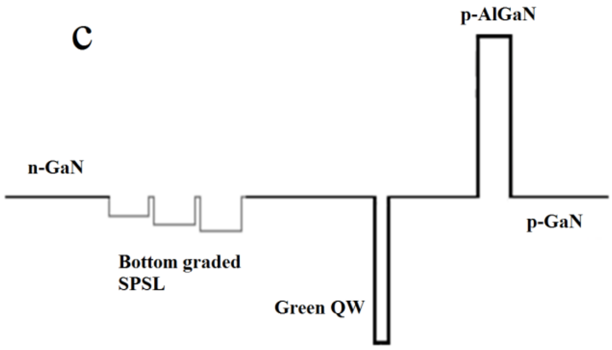


Figure 1. Conduction band diagram of the White LED structure (a); Blue LED structure (b) and Green SQW structure (c).

The structures were processed as TM-27 (680x560 mcm^2) and MK-24 (1310x1310 mcm^2) chips developed by Scientific-Technological Centre of Microelectronics and Submicrometer Heterostructures, Russian Academy of Science. The chip design and its optical properties were carefully described previously.[14]

A. Experimental details

As a basic experimental method we have employed T-IDEL.[15] IQE, IE and LEE were evaluated by fitting procedure with the ABC model and following the method reported in our previous work.[16]
A Labsphere CDS-600 spectrometer accompanied with LightMtrx software and helium closed-cycle cryostat Janis CCS-450 were used for this purpose. In order to determine EQE, we measured the electroluminescence (EL) intensity at various temperatures from 13 to 300 K in a wide range of operating currents, from 10^{-8} to 1 A. To cover a large range of the measured radiant fluxes, from 1 nW to 0.1 W, we used variation of the photodetector exposure time from 1 ms to 5 s and ND1-4 filters for light intensity attenuation. EQE was measured first in the integrating sphere and then in the cryostat at room temperature (RT); after that the optical alignment was not changed at other temperatures. In order to obtain absolute values of EQE for temperatures other than RT, we used the normalization factors calculated for the RT data. The absence of any media adjacent to the chip surface is an essential for correct temperature- and intensity-dependent electroluminescence (T-IDEL) measurements.

To examine CCT tunability of the white LED we measured emission spectra in the CW and pulse modes using current pulses from 100 ns to 100 μs and varying duty cycle from 1% to 95%. The current-voltage (I-V) characteristics of the LEDs were measured by the Keithley 4200 semiconductor characterisation system at the room temperature.

Results and Discussion

The Figure 2 shows I-V characteristic measured with MK-24 white LED chip at room temperature. For the analysis we used the advanced fitting procedure with one parallel and one series resistance equivalent scheme. The parameters obtained from the fitting are shown at the picture. Parallel Resistance (Rp) = 170 MOhm Series Resistance (Rs) = 25 Ohm; Ideality Factor (f) = 4.3; Saturation Current (Io) = 1.5*10^{-14} A. Such a high ideality factor usually can be attributed to the undoped GaN barriers inside the active region.[17,18]

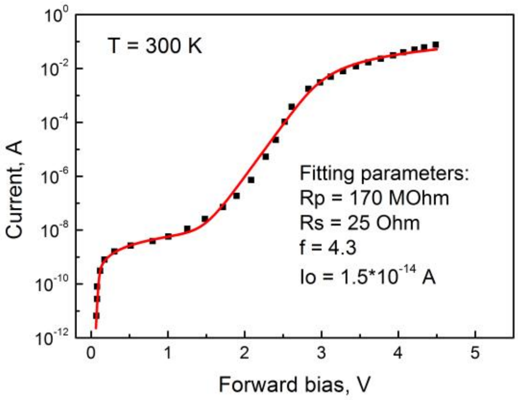


Figure 2. Current-Voltage characteristic of the white LED (symbols) and fitting function (line).

The Figure 3 (A, B, C) shows the separately measured EQE of the monolithic white LED vs. current at different temperatures. The Figure 3 (D) presents evaluated Internal and Injection Efficiencies (IE) vs. temperature. The white EQE is resulted from the balance of the green and blue bands efficiencies. From this curves we can also note that when the blue band IQE and IE strongly depend on the temperature, the green ones are almost constant.

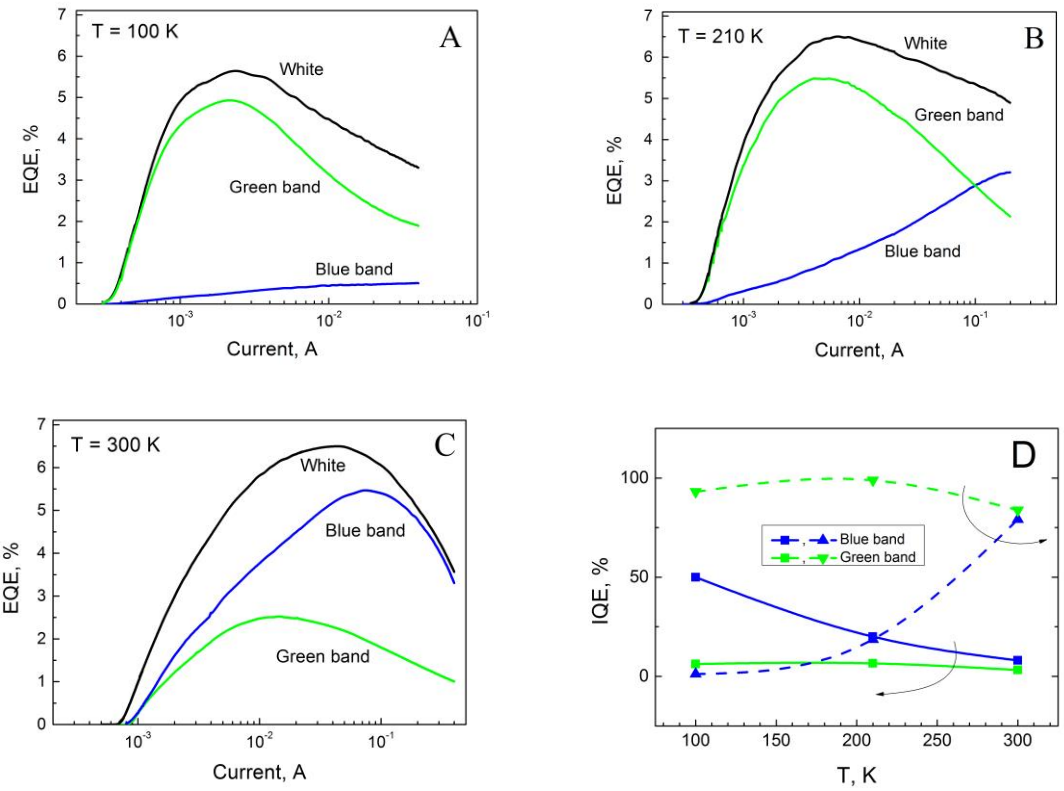


Figure 3. EQE of the monolithic white LED vs. currents at different temperatures: A - 100K; B - 210K and C - 300K; D presents evaluated Internal and Injection Efficiencies (IE) vs. temperature.

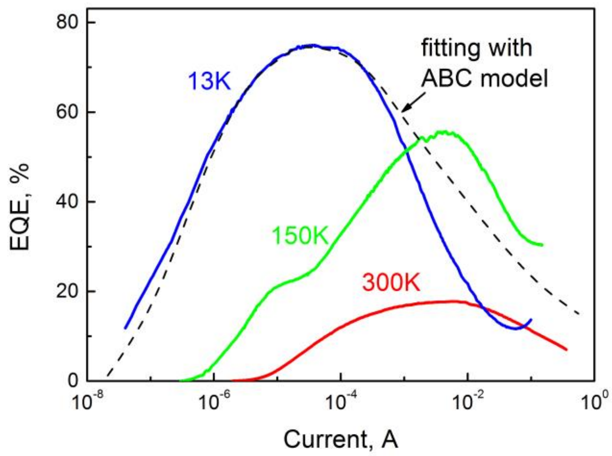


Figure 4. EQE of the blue (459nm) emitting LED vs. currents at different temperatures and fitting with ABC model (dash line).

Figure 4 shows EQE vs. driving current measured at three temperatures. The twin-peak shape of 150K curve and narrow dome 13K curve testify about In compound fluctuations in QW layers. It leads to deviations of the experimental curve from the classic ABC model. From the other hand having only one classic shaped peak IQE, IE and LEE estimation could be possible. Here we took 13K curve as the most suitable for fitting with ABC model. Maximal IQE(13K) was estimated as 87% at 0.08 A/cm^2. Hence room temperature IQE can be estimated as 21% in the maximum. Assuming the blue LED IE at the maximum as 100% we can obtain LEE as 86% from the fitting procedure.[16] This value looks overestimated for at least 20% from the common sense. From the other hand the value is very similar to the reflectivity obtained with 3D ray-tracing estimation by A. E. Chernyakov et.al.[14] In that paper authors studied light propagation and extraction from the LED die by 3D ray-tracing accounting for the optical properties of all elements of the chip design. In particular, the reflectivity of the n- and p-electrodes was assumed to be of 87% at normal incidence. Considering our chip design we can assume the electrode reflectivity mostly contribute to the whole light extraction, so the real LEE should be about 15-20% less than 87%.

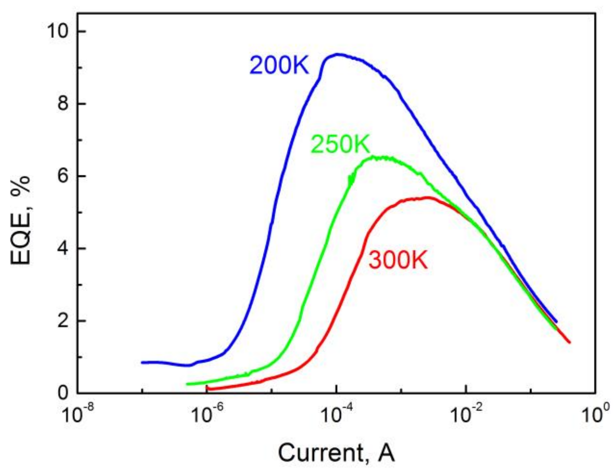
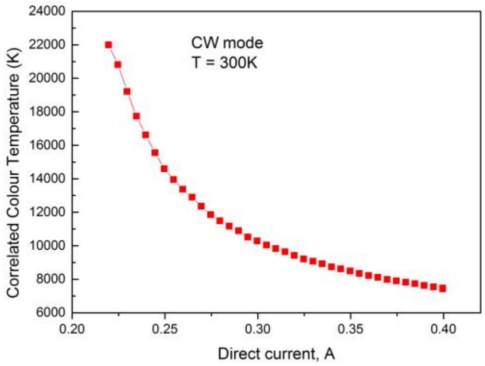


Figure 5. EQE of the green (526 nm) emitting LED vs. currents at different temperatures

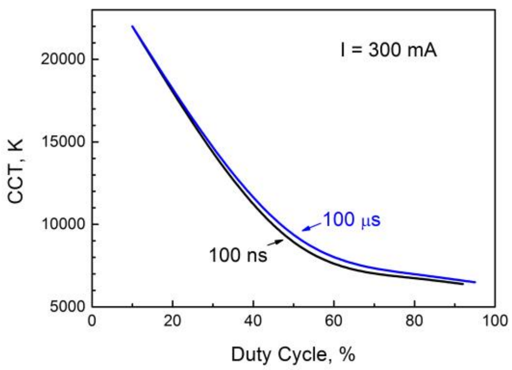
The green LED IQE is 45% from fitting, LEE = 12% assuming 100% IE, but it looks underestimated, so if take LEE as 86% we can obtain IE = 14% at measured EQE = 5.4% in maximum.

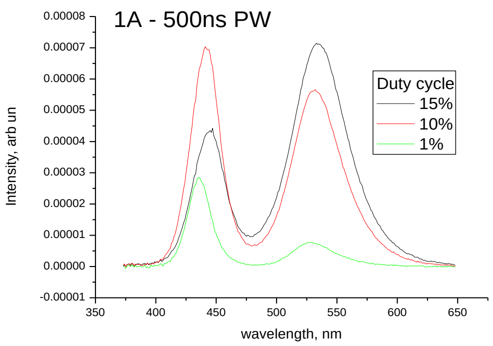
CCT and spectral data analysis.

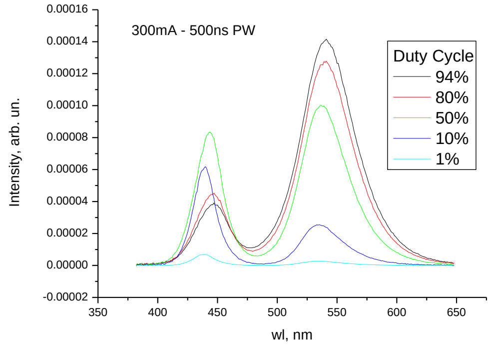
Direct Current (CW mode)



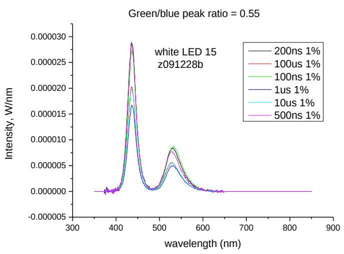
Pulse mode

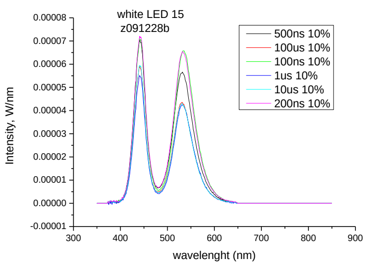


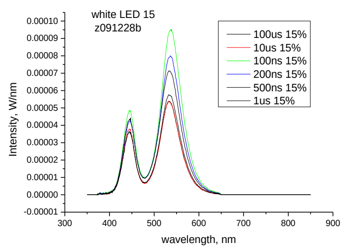


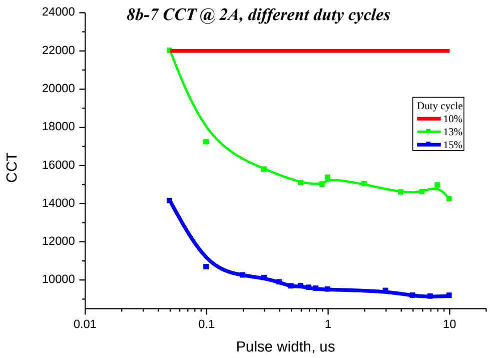


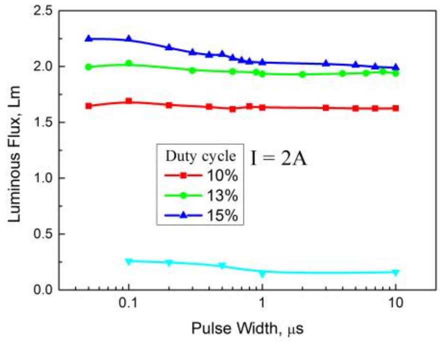
Pulse mode 2A; Duty Cycle: 1-10-15%

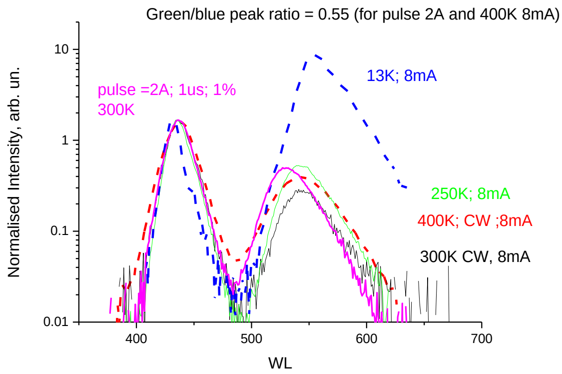


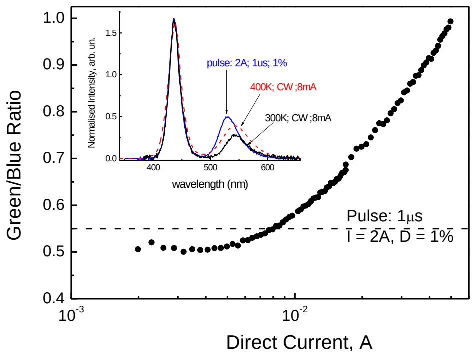












It is noticeable that green/blue peaks ratio has the same value for 400K 10mA as 1% Duty Cycle. If suppose the spectra transformation caused by overheating, that means the active region works at as high temperature as 127°C at 2A driving current, 1% Duty cycle and 200 ns – 1us pulse width.

Acknowledgment

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REFERENCES

[1] Narukawa, Y., Ichikawa M., Sanga D., Sano M., and Mukai T., "White light emitting diodes with super high luminous efficacy," J. Phys. D: Appl. Phys. 43, 354002, (2010).
[2] Schubert E. F., and Kim J. K., Science, "Solid-state light source getting smart," Science 308 (5726), 1274-1278 (2005).
[3] Schubert E. F., [Light-Emitting Diodes], Cambridge University Press, Cambridge, England, (2003).
[4] Kim, T., "A nanopyramid structure for monolithic white-light LEDs," SPIE Newsroom, Jan. 30 2013. https://spie.org/x92145.xml.

[5] Damilano, B., Grandjean, N., Pernot, C. and Massies, J., "Monolithic white light emitting diodes based on InGaN/GaN multiple-quantum wells," Jpn. J. Appl. Phys. 40, L918–L920 (2001).
[6] Damilano, B., Trad, N., Brault, J., Demolon, P., Natali, F. and Massies, J., "Colour control in monolithic white light emitting diodes using a (Ga,In)N/GaN multiple quantum well light converter," Phys. Status Solidi A 209(3), 465-468(2012).
[7] Lu, C. F., Huang, C. F., Chen, Y. S., Shiao, W. Y., Chen, C. Y., Lu, Y. C. and Yang C. C., "Phosphor-Free Monolithic White-Light LED," IEEE Journal of Selected Topics in Quantum Electronics 15(4), 1210-1217 (2009).
[8] Ko, Y.-H., Kim, J.-H., Jin, L.-H., Ko, S.-M., Kwon, B.-J., Kim, J., Kim, T., Cho, Y.-H., "Electrically driven quantum dot/wire/well hybrid light-emitting diodes," Adv. Mater. 23(45), 5364-5369 (2011).
[9] Oh, J. H., Oh J. R., Park H. K., Sung, Y.-G., and Do, Y. R., "Highly-efficient, tunable green, phosphor-converted LEDs using a long-pass dichroic filter and a series of orthosilicate phosphors for tri-color white LEDs," Optics Express 20(S1), A1-A12 (2012).
[10] Yu, C., Lirong, H. and Shanshan, Z., "Monolithic white LED based on $Al_xGa_{1-x}N/In_yGa_{1-y}N$ DBR resonant-cavity," Journal of Semiconductors 30(1), 014005 (2009).
[11] Tsatsulnikov, A. F., Lundin, W. V., Sakharov, A. V., Zavarin, E. E., Usov, S. O., Nikolaev, A. E., Kryzhanovskaya, N. V., Synitsin, M. A., Sizov, V. S., Zakgeim, A. L. and Mizerov, M. N., "A monolithic white LED with an active region based on InGaN QWs separated by short-period InGaN/GaN superlattices," Semiconductors 44(6), 808–811 (2010).
[12] Tsatsulnikov, A. F., Lundin, W. V., Sakharov, A. V., Zavarin, E. E., Usov, S. O., Nikolaev, A. E., Kryzhanovskaya, N. V., Sizov, V. S., Synitsin, M. A., Yakovlev, E. V., Chernyakov, A. E., Zakgeim, A. L., Cherkashin, N. A. and Hytch, M., "InGaN/GaN short-period superlattices: synthesis, properties, applications," Phys. Status Solidi C 8(7–8), 2308–2310 (2011).
[13] Lundin W.V., Nikolaev A.E., Sakharov A.V., Zavarin E.E., Valkovskiy G.A., Yagovkina M.A., Usov S.O., Kryzhanovskaya N.V., Sizov V.S., Brunkov P.N., Zakgeim A.L., Cherniakov A.E., Cherkashin N.A., Hytch M.J., Yakovlev E.V., Bazarevskiy D.S., Rozhavskaya M.M., Tsatsulnikov A.F., "Single quantum well deep-green LEDs with buried InGaN/GaN short-period superlattice," Journal of Crystal Growth 315, 267 (2011).
[14] Chernyakov, A. E., Bulashevich, K. A., Karpov, S. Yu. and Zakgeim, A. L., "Experimental and theoretical study of electrical, thermal, and optical characteristics of InGaN/GaN high-power flip-chip LEDs," Phys. Status Solidi A 210(3), 466–469 (2013).
[15] M. Peter, A. Laubsch, W. Bergbauer, T. Meyer, M. Sabathil, J. Baur, and B. Hahn, "New developments in green LEDs," Phys. Stat. Solidi A 206 (6), 1125-1129 (2009).
[16] Titkov, I. E., Sannikov, D. A., Park, Y.-M. and Son, J.-K., "Blue light emitting diode internal and injection efficiency," AIP Advances 2, 032117 (2012).
[17] APPLIED PHYSICS LETTERS 94, 081113 2009
[18] JOURNAL OF APPLIED PHYSICS VOLUME 94, NUMBER 4