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395 nm Light-Emitting Diode with 647 mW Output Power Realized Using a Double p-Type Aluminum Composition Gradient with Polarization-Induced Hole Doping

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ABSTRACT

Three p-type layer structures, i.e. a p-GaN layer, a short-period superlattice (SL) insertion layer, and a polarization-induced hole-doped double-aluminum composition gradient layer, were compared in terms of their performance in 395 nm high-power light-emitting diodes (LEDs). The device with the polarization-induced hole-doped double-aluminum composition gradient layer has an operating voltage of 3.34 V and a wall-plug efficiency of 55.3% under a 350 mA injection current. Moreover, devices with the polarization-induced hole-doped double-aluminum composition gradient layer structure have better optical output power than devices with a short-period SL inserted in p-GaN.

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395nm LED; Al composition gradient layer; superlattice

1. Introduction

Light-emitting diodes (LEDs) based on multiple quantum wells (MQWs) of AlGaN/GaN and GaN/InGaN operating in the near-UV wavelength range of 320–400 nm are of interest for applications in high-density optical data storage, UV-enabled credit card security, UV lithography, sensing, medical equipment sterilization, and security [1–5]. Development of UV LEDs with high wall-plug efficiency and high output power has become increasingly important. In recent years, due to the lack of a highly conductive p-type AlGaN layer, low device conversion efficiency has remained a serious problem in high-power UV LEDs [6]. In addition, current leakage in high-power UV LEDs is detrimental to optical and electrical performance and requires innovative design optimization of device technology and the metal-organic chemical vapor deposition (MOCVD) material growth process. Conventional Mg-doped p-AlGaN devices exhibit poor optical and electrical performance, such as a low optical output power and a high operating voltage [7].

Many research institutes and universities have conducted many studies on improving the hole concentration of p-type layers of LEDs, reducing the resistance of p-type layers, and improving the performance of LEDs. Yu et al. [8] found that the introduction of

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Mg-doped AlGaN/InGaN superlattice (SL) electron blocking layers can improve the operating voltage, output power, and efficiency of GaN-based LEDs. The performance of deep ultraviolet LEDs manufactured by Al Tahtamouni et al. [9] using a Mg SL has been significantly improved, as manifested by the enhanced light intensity and output power and reduced turn-on voltage. The increased performance is attributed to the enhanced blocking of electron overflow and the enhancement of hole injection. In addition, in 2010, Simon et al. [10] proposed the use of a polarization field formed by a hierarchical elemental composition rather than thermal energy to ionize the Mg acceptor, leading to a high-density three-dimensional hole concentration of up to $2 \times 10^{18}\,cm^{-3}$. By applying this technique to an LED, the hole concentration in the active region is expected to be improved, and the interface band structure is smoothed. Wang et al. [11] performed polarization doping of the doped hole concentration and modified the band structure to eliminate band bending in the last QB/p-type layer interface and reduce the electrostatic field in the active region. The segmented aluminum composition graded layer had a stronger hole injection capability.

The purpose of both processes is to improve the hole injection efficiency of the p-type layer, thereby improving the luminous efficiency. However, the effectiveness of the two processes in improving the wall-plug efficiency of high-power LEDs has rarely been compared.

In this paper, we fabricate three sets of samples by controlling the thickness of the p-type layer and the doping concentration. The p-type layer of sample A is conventional Mg-doped p-GaN. A 60 nm short-period AlGaN/GaN SL is inserted into the p-type layer to obtain sample B. Sample C has two 90 nm thick polarized-doped aluminum composition layers as the p-type layer. An atomic force microscope (AFM) was used to detect the surface morphology of the epitaxial wafers. The electroluminescence (EL) spectra and luminescence characteristics (L–I) of the fabricated LEDs were measured and discussed.

2. Experimental

In this paper, an LED chip is grown on a c-plane patterned sapphire substrate by MOCVD. The sample devices used in the experiment were prepared by Jiangsu Ginjoe Semiconductor Co., Ltd., including the growth of LED epitaxial wafers and the die processing of the later devices, as were the performance tests of the chips and devices. This test uses German commercial Aixtron MOCVD equipment. Trimethylgallium is used for the u-GaN layer and the n-GaN layer of the LED, and for the other thin layer structures, such as quantum wells and SLs, we use triethyl gallium, taking into account the precise control of the growth rate and quality of the growth material.

To compare the epitaxial crystal quality and luminescence properties of the devices, we fabricated two sets of samples for comparison with sample A, sample B, and sample C. Figure 1 shows the sample LED epitaxial chip structure. The patterned sapphire substrate was heated for 10 min at a high temperature of 1080 °C for surface cleaning. Then, an approximately 2.5 µm u-GaN buffer layer was grown at a high temperature, and a 2 µm thick Si-doped n-GaN layer was grown. Then, an 8-cycle quantum well prelattice structure was obtained, in which the barrier layer is doped with Si, and the thicknesses of each period of GaN and $In_{0.05}Ga_{0.95}$ are 7 nm and 1 nm, respectively.

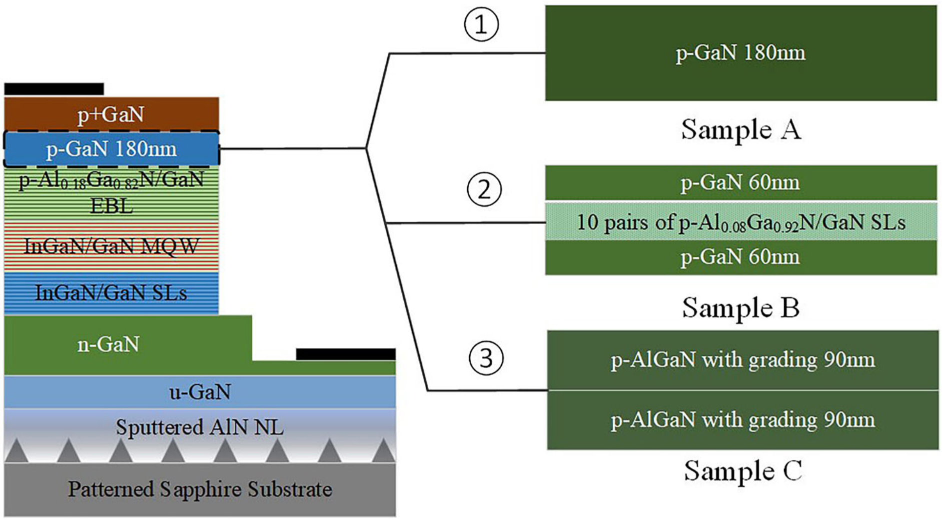

Figure 1. Schematic illustration of the 395 nm UV LED epitaxial structure.

The GaN/$In_{0.05}Ga_{0.95}N$ MQW layer has thicknesses of 14 nm and 1.5 nm for the barrier layer and the quantum well layer, respectively, and the growth temperatures were 740 °C and 850 °C. On top of the MQWs is a 5-period p-type 3.5 nm-$Al_{0.16}Ga_{0.84}N$/2.5 nm-GaN SL electronic barrier layer (EBL) with a doping concentration of $5 \times 10^{18}\,cm^{-3}$. The p-GaN layer in sample A is GaN with a 180 nm p-doping concentration of $5 \times 10^{17}\,cm^{-3}$.

In sample B, a 60 nm portion of the p-GaN layer in comparative sample A was replaced with a p-type SL layer. The number of p-AlGaN/GaN SL periods is 10, and the thicknesses of GaN and $Al_{0.08}Ga_{0.82}$ are 2.5 nm and 3.5 nm, respectively, which are short-period SLs.

In sample C, the 180 nm portion of the p-GaN layer in comparative sample A was replaced with a double-aluminum linear composition gradient layer. Each gradient layer of the aluminum component has a thickness of 90 nm. The aluminum composition in each layer varies from 8% to 0%. We use a double-aluminum composition gradient layer to promote the accumulation of holes to avoid the formation of excessively polarized positive charges at the interface between the multilevel gradient AlGaN layers.

After the epitaxial wafer was completed, the sample A, B, and C epitaxial wafers were processed into LED devices with a device area of 1.27 mm × 1.27 mm by a standardized chip die process. The anode electrode was plated with CrNiAu alloy on the InSnO (ITO) transparent conductive layer. The cathode electrode was plated with CrNiAu alloy.

Finally, experimental sample chips were subjected to EL tests using a Wilmington LED-617 photoelectric tester and a UV-100 test probe.

3. Results and Discussion

As shown in Figure 2, after epitaxy of the sample, we used AFM to analyze the surface morphology of the short-wavelength UV LED epitaxial chips to characterize the

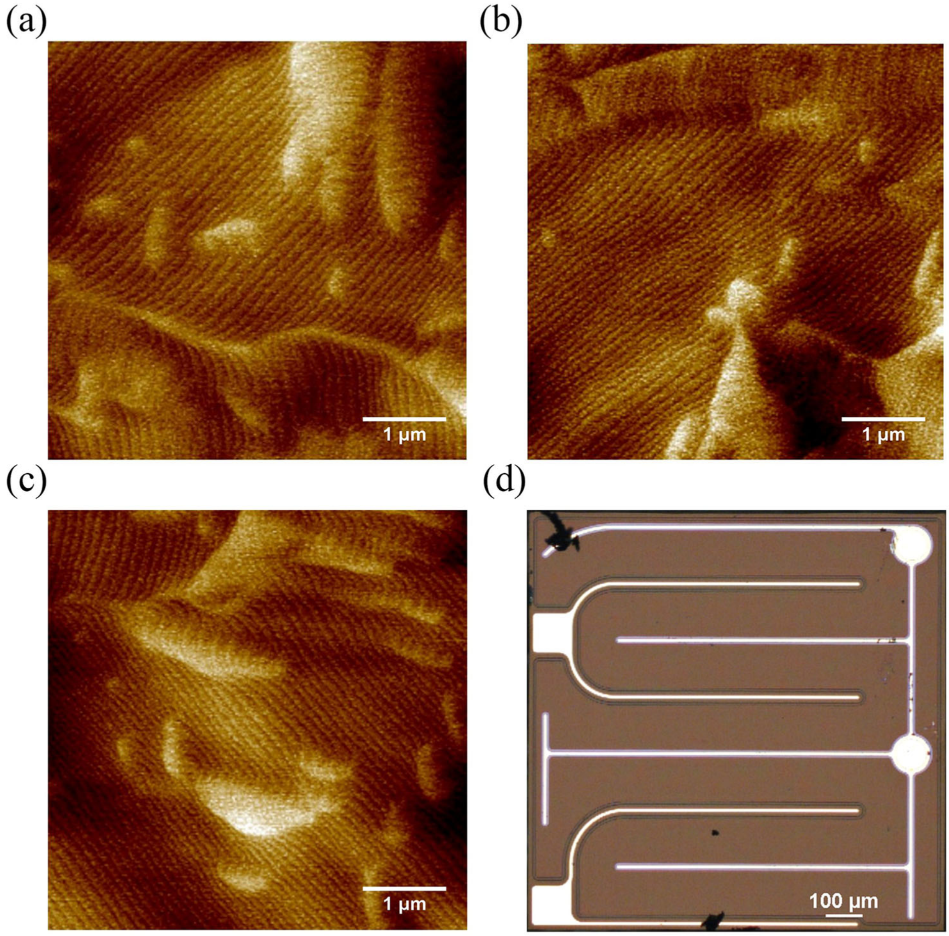

Figure 2. (a)–(c) AFM images of samples A, B, and C with a detection area of 5×5 μm^2. (d) Optical microscope picture of an LED chip.

epitaxial growth crystallization quality of the chip materials. Figure 2(a–c) show two-dimensional surface topography views of the sample A, B, and C epitaxial wafers, respectively. The surface roughness RMS of the three groups of 5 μm × 5 μm samples was 0.61 nm, 0.42 nm, and 0.54 nm, respectively. The surface roughness of samples B and C was lower than that of sample A, but the overall difference was not large.

The three sets of samples were fabricated into 1.27 mm × 1.27 mm chips, as shown in Figure 2(d); from each set, 20 samples were randomly taken, and the average output power of each was tested from 50 to 400 mA. The results are shown in Figure 3(a). At a charge current of 350 mA, the output powers of samples B and C can reach 567.7 mW and 646.6 mW, respectively, which are significantly higher than that with the conventional p-GaN intercalation layer of 462.1 mW. Sample C with the p-type aluminum composition gradient layer can be operated at a current of 350 mA and an operating voltage of 3.34 V.

At this current, the wall-plug efficiency of sample C can reach 55.3%, and the wall-plug efficiency of samples C and B is improved by 16.9% and 10.2%, respectively,

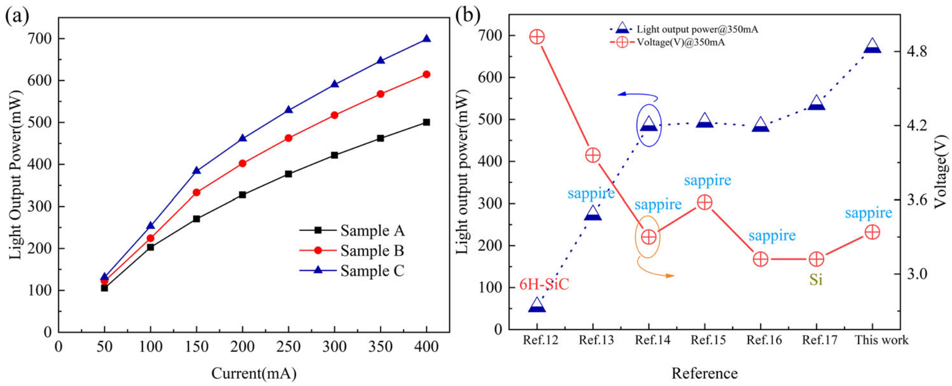

Figure 3. (a) L–I characteristics of samples A, B, and C. (b) State-of-the-art properties of GaN-based near-UV LEDs.

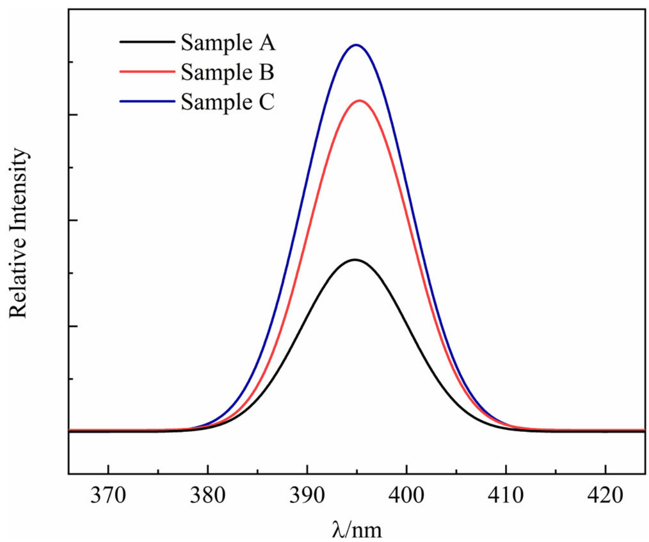

Figure 4. EL spectra of samples A, B, and C at 200 mA.

compared with sample A. Moreover, the performance of the near-UV LED chips achieved in this work is better than the reported state-of-the-art values [12–17], as presented in Figure 3(b).

Figure 4 shows the room-temperature EL spectra of the three sets of UV LED epitaxial wafer samples. The peak emission wavelengths of the three UV LED epitaxial wafers are approximately 395 nm, and the wavelength uniformity is good. With the insertion of the polarization-doped aluminum composition gradient layer, the EL peak intensity is greatly enhanced.

As shown in Figure 5, we selected three epitaxial wafers in the same position from three groups of samples. Device performance-related tests are performed on all the dies prepared on each epitaxial wafer. In Figure 5(a), we tested the optical output power of the die at a 350 mA injection current. From the figure, we can see that the consistency of the optical output power of the die of sample C and sample B is significantly higher

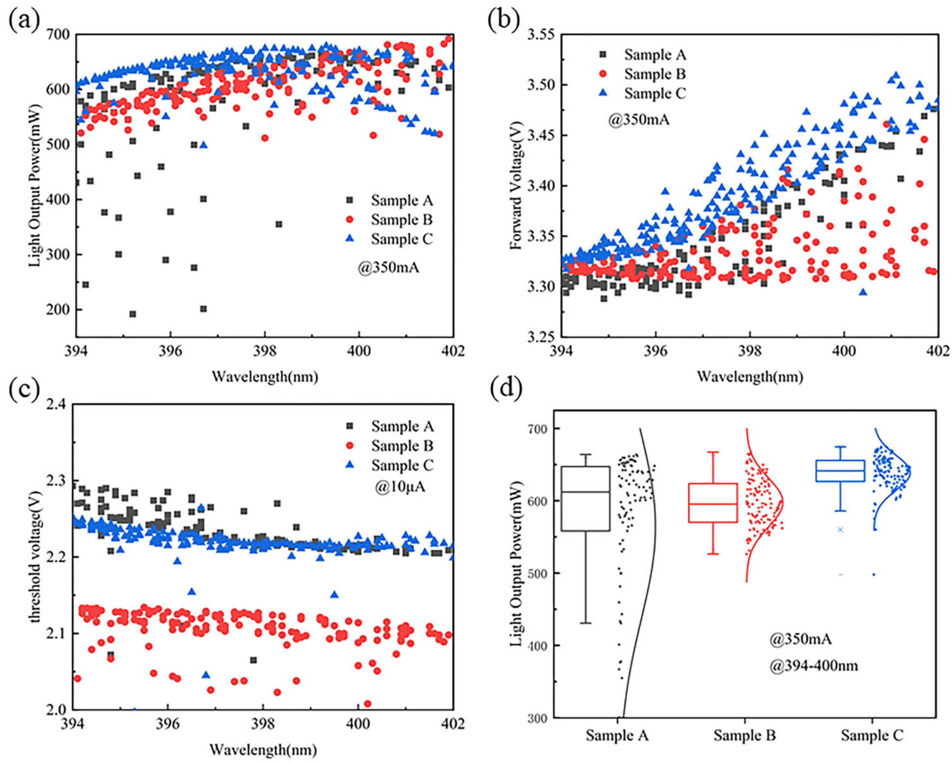

Figure 5. (a) Optical output power of samples A, B, and C. (b) Forward working voltage of samples A, B, and C. (c) Threshold voltage of samples A, B, and C.

than that of sample A. Sample C is in the range of 394–398 nm with a smaller emission wavelength from 395 nm, and the light output power is the maximum among the three groups of samples. This result also proves the effectiveness of introducing a double-aluminum component graded layer in 395 nm near-ultraviolet LEDs to improve device brightness.

In Figure 5(b), we tested the operating voltage of the die at 350 mA injection current. In Figure 5(c), we tested the turn-on voltage of the die under a low injection current of 10 μA. Under the same injection current density, the forward working voltage of sample C is approximately 0.1 V higher than that of sample B. This gap is even more pronounced at low current density injection conditions. The turn-on voltage of sample C is slightly lower than that of sample A but is significantly higher than that of sample B with a p-type SL insertion layer. Sample B has an ultralow turn-on voltage mainly due to changes in the conduction and valence band edges of the GaN and AlGaN materials in the [18–22] SL structure. The GaN layer in the SL is thermally excited by the acceptor. It can be ionized, and the acceptor in the $Al_xGa_{1-x}N$ material is very close to the valence band edge of GaN, which greatly reduces the activation energy of the acceptor in the material, which is easier to ionize than the AlGaN bulk material.

So as to prove the rigorous conclusion that the structure of sample C can improve the light output power performance of near-ultraviolet LED devices, we used statistical methods to discuss the die made of three groups of samples. Select ordinary working LED chips with an emission wavelength in the range of 394–400nm under an injection current of 350 mA. The light output power of each LED chip at 350 mA was recorded, and the box-plot diagram and the normal distribution curve were drawn in groups to obtain Figure 5(d). As can be seen from Figure 5(d), we can grasp that the consistency of sample C is significantly higher than that of sample B and sample A. And the number of abnormal points of sample B and sample C are close to each other, and both are smaller than those of sample A. This illustrates that sample C can meet the requirements of industrial production. The median normal distribution of sample C is 641.3 mV, which is similar to the value obtained by calculating the average value in Figure 3(a). This demonstrates that the double-aluminum composition gradient layer we applied in 395 nm near-ultraviolet LED has the effect of improving the light output power.

4. Conclusions

In summary, the light output power of LEDs can be significantly improved by using a p-type double-aluminum component gradient layer structure in a near-UV LED structure. At the same time, of having higher light output power, the turn-on voltage will also increase compared to near-UV LEDs with SL insertion layers. The near-ultraviolet LED with a p-type double-aluminum component gradient layer structure can be applied to applications that require higher light emission brightness.

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References

1. T. Takano *et al.*, Deep-ultraviolet light-emitting diodes with external quantum efficiency higher than 20% at 275 nm achieved by improving light-extraction efficiency, *Appl. Phys. Express* **10** (3), 031002 (2017). DOI: 10.7567/APEX.10.031002.
2. H. Hirayama *et al.*, 227 nm AlGaN light-emitting diode with 0.15 mW output power realized using a thin quantum well and AlN buffer with reduced threading dislocation density, *Appl. Phys. Express* **1**, 051101 (2008). DOI: 10.1143/APEX.1.051101.
3. J. Piprek, Ultra-violet light-emitting diodes with quasi acceptor-free AlGaN polarization doping, *Opt. Quant. Electron.* **44** (3–5), 67 (2012). DOI: 10.1007/s11082-011-9509-0.
4. J. Han *et al.*, AlGaN/GaN quantum well ultraviolet light emitting diodes, *Appl. Phys. Lett.* **73** (12), 1688 (1998). DOI: 10.1063/1.122246.
5. Y. Taniyasu, M. Kasu, and T. Makimoto, An aluminium nitride light-emitting diode with a wavelength of 210 nanometres, *Nature* **441** (7091), 325 (2006). DOI: 10.1038/nature04760.
6. H. Hu *et al.*, Effects of GaN/AlGaN/sputtered AlN nucleation layers on performance of GaN-based ultraviolet light-emitting diodes, *Sci. Rep.* **7**, 44627 (2017). DOI: 10.1038/srep44627.
7. J. Li *et al.*, Optical and electrical properties of Mg-doped *p*-type $Al_xGa_{1-x}N$, *Appl. Phys. Lett.* **80** (7), 1210 (2002). DOI: 10.1063/1.1450038.
8. C. T. Yu *et al.*, Effects of InGaN layer thickness of AlGaN/InGaN superlattice electron blocking layer on the overall efficiency and efficiency droops of GaN-based light emitting diodes, *Opt. Express* **22** (S3), A663 (2014). DOI: 10.1364/OE.22.00A663.

9. T. Al Tahtamouni, J. Lin, and H. Jiang, Effects of Mg-doped AlN/AlGaN superlattices on properties of p-GaN contact layer and performance of deep ultraviolet light emitting diodes, *AIP Adv.* **4** (4), 047122 (2014). DOI: 10.1063/1.4871996.
10. J. Simon *et al.*, Polarization-induced hole doping in wide-band-gap uniaxial semiconductor heterostructures, *Science* **327** (5961), 60 (2010). DOI: 10.1126/science.1183226.
11. L. Y. Wang *et al.*, Efficiency enhancement of ultraviolet light-emitting diodes with segmentally graded p-type AlGaN layer, *Chinese Phys. B.* **28** (1), 018503 (2019). DOI: 10.1088/1674-1056/28/1/018503.
12. W. Lin, S. Li, and J. Kang, Near-ultraviolet light emitting diodes using strained ultrathin InN/GaN quantum well grown by metal organic vapor phase epitaxy, *Appl. Phys. Lett.* **96** (10), 101115 (2010). DOI: 10.1063/1.3360199.
13. D. S. Meyaard *et al.*, GaInN light-emitting diodes using separate epitaxial growth for the p-type region to attain polarization-inverted electron-blocking layer, reduced electron leakage, and improved hole injection, *Appl. Phys. Lett.* **103** (20), 201112 (2013). DOI: 10.1063/1.4829576.
14. P. Tao *et al.*, Enhanced output power of near-ultraviolet LEDs with AlGaN/GaN distributed Bragg reflectors on 6H–SiC by metal-organic chemical vapor deposition, *Superlattices Microstruct.* **85**, 482 (2015). DOI: 10.1016/j.spmi.2015.05.035.
15. C. H. Tien *et al.*, ITO/nano-Ag plasmonic window applied for efficiency improvement of near-ultraviolet light emitting diodes, *Phys. Status Solidi A* **214** (3), 1600609 (2017). DOI: 10.1002/pssa.201600609.
16. J. Xu *et al.*, Light-extraction enhancement of GaN-based 395 nm flip-chip light-emitting diodes by an Al-doped ITO transparent conductive electrode, *Opt. Lett.* **43** (11), 2684 (2018). DOI: 10.1364/OL.43.002684.
17. Y. Li *et al.*, High-performance vertical GaN-based near-ultraviolet light-emitting diodes on Si substrates, *J. Mater. Chem. C* **6** (42), 11255 (2018). DOI: 10.1039/C8TC04477E.
18. Y. C. Yeo, T. C. Chong, and M. F. Li, Electronic band structures and effective-mass parameters of wurtzite GaN and InN, *J. Appl. Phys.* **83** (3), 1429 (1998). DOI: 10.1063/1.366847.
19. M. Katsuragawa *et al.*, Thermal ionization energy of Si and Mg in AlGaN, *J. Cryst. Growth* **189–190**, 528 (1998). DOI: 10.1016/S0022-0248(98)00345-5.
20. E. F. Schubert, W. Grieshaber, and I. D. Goepfert, Enhancement of deep acceptor activation in semiconductors by superlattice doping, *Appl. Phys. Lett.* **69** (24), 3737 (1996). DOI: 10.1063/1.117206.
21. H. Sakai *et al.*, Stimulated emission with the longest wavelength in the blue region from GaInN/GaN multi-quantum well structures, *J. Cryst. Growth* **189–190**, 831 (1998). DOI: 10.1016/S0022-0248(98)00304-2.
22. P. Kozodoy *et al.*, Enhanced Mg doping efficiency in $Al_{0.2}Ga_{0.8}N$/GaN superlattices, *Appl. Phys. Lett.* **74** (24), 3681 (1999). DOI: 10.1063/1.123220.