AIP ADVANCES **4**, 047122 (2014)

Effects of Mg-doped AlN/AlGaN superlattices on properties of p-GaN contact layer and performance of deep ultraviolet light emitting diodes

T. M. Al tahtamouni,[1,a] J. Y. Lin,[2] and H. X. Jiang[2]
[1]*Department of Physics, Yarmouk University, Irbid 21163, Jordan*
[2]*Department of Electrical and Computer Engineering, Texas Tech University, Lubbock, Texas 79409, USA*

(Received 14 February 2014; accepted 9 April 2014; published online 17 April 2014)

Mg-doped AlN/AlGaN superlattice (Mg-SL) and Mg-doped AlGaN epilayers have been investigated in the 284 nm deep ultraviolet (DUV) light emitting diodes (LEDs) as electron blocking layers. It was found that the use of Mg-SL improved the material quality of the p-GaN contact layer, as evidenced in the decreased density of surface pits and improved surface morphology and crystalline quality. The performance of the DUV LEDs fabricated using Mg-SL was significantly improved, as manifested by enhanced light intensity and output power, and reduced turn-on voltage. The improved performance is attributed to the enhanced blocking of electron overflow, and enhanced hole injection. © *2014 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution 3.0 Unported License.* [http://dx.doi.org/10.1063/1.4871996]

Deep ultraviolet (DUV) light-emitting diodes (LEDs) have attracted much attention recently due to a wide variety of potential applications including air and water purification, surface disinfection, UV curing, and medical phototherapy.[1,2] Al-rich AlGaN alloys are ideal materials to realize deep ultraviolet (DUV) emitters with wavelengths shorter than 300 nm due to its tunable bandgap between 3.4 and 6.2 eV. However, there are several key issues in achieving high-efficiency AlGaN-based UV LEDs, and one of which is the electron overflow from the active region into the p-GaN contact layer. Due to the difference in electron and hole mass in nitride semiconductors, electrons tend to escape from the active region, whereas holes are poorly injected into the active region.[3] Electron overflow is a severe problem because leaked electrons may recombine with holes in the p-type GaN predominantly via nonradiative processes.[4–6] Electrons may also escape the active region through tunneling, further reducing the emission efficiency. Therefore, inclusion of Mg doped AlGaN electron blocking layer (EBL) between the active region and p-type GaN layer is essential to prevent electron overflow. The AlGaN EBL with high Al composition plays an important role of increasing the density of free electrons in the active region by blocking the injected electron from overflowing into the p-region thereby enhancing the radiative efficiency.[7,8] However, p-type AlGaN with a high Al content generally suffers from low hole concentration, which is caused by the high Mg acceptor activation energy.[9] One promising approach in circumventing low p-type conductivity in $Al_xGa_{1-x}N$ epilayers is the incorporation of Mg-doped superlattices (SLs).[10–14] These periodic structures exploit the large polarization fields in wurzite III-nitrides to achieve enhanced hole activation and free hole concentrations.[15] In a SL structure comprising layers of alternately higher and lower Al composition, $Al_xGa_{1-x}N/Al_yGa_{1-y}N$ with $x > y$, Mg atoms in the $Al_xG_{1-x}N$ are ionized and the holes tend to accumulate in the $Al_yGa_{1-y}N$ layers. This design allows both vertical and lateral hole transport.[16] Other than improving the lateral and vertical conductivity, the SL EBL, which is adjacent to the multiple quantum wells (MQW), can partially fill the dislocation-related

[a]Electronic mail: talal@yu.edu.jo

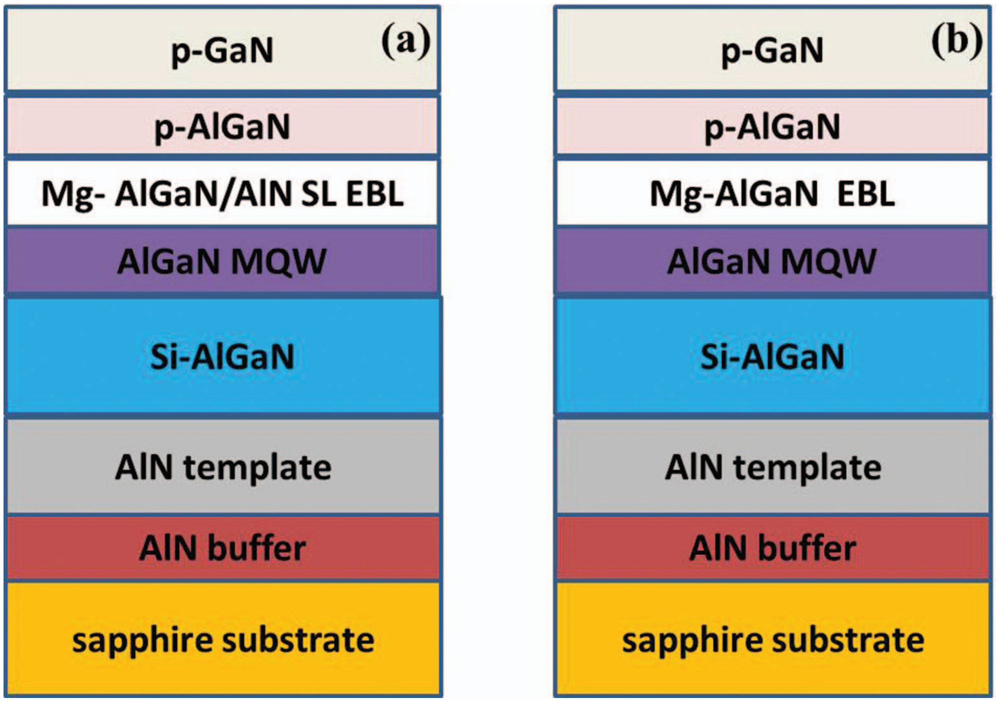

FIG. 1. The schematic diagrams of 284 nm DUV LED structures incorporating Mg-doped (a) AlN/AlGaN SL EBL and (b) AlGaN EBL.

pits that occur on the surface of the MQW and that are due to the strain. If these dislocation-related pits are not partially suppressed, they will eventually result in surface pits associated with threading dislocations that intersect the MQW,[17] thereby reducing the crystal quality and conductivity of the contact layer, which will be reflected on the performance of DUV LED. Much of the reported work on these structures has focused on GaN/AlGaN p-SLs with effective band gaps suitable for near UV and visible device applications.[18] The development of Mg-doped short period $Al_xGa_{1-x}N/Al_yGa_{1-y}N$ SLs using metal organic chemical vapor deposition (MOCVD) growth has also been realized.[19] The combined electrical and optical characteristics of these p-SLs suggested that they could be potential candidates for wide band gap p-type cladding layers in DUV optoelectronic device structures.[16,19]

In this work, we investigate the effects of incorporating Mg-doped AlN/AlGaN SL structures as EBL on the p-GaN contact layer and the performance of DUV LEDs via MOCVD growth. Atomic force microscopy (AFM) was used to probe the surface morphology, x-ray diffraction (XRD) was used to determine the Al content of the epilayers as well as the crystalline quality. The electroluminescence (EL) spectra, current-voltage (I–V) characteristics, and light emission characteristics (L-I) of fabricated LEDs were measured and discussed. The characteristics of the DUV LEDs ($\lambda = 284$ nm) with Mg-doped AlN/AlGaN SL EBL have been studied and compared to DUV LEDs with Mg-doped AlGaN EBL. The DUV LEDs fabricated using Mg-doped AlN/AlGaN SL EBL exhibited improved performance as evidenced by higher EL intensities, enhanced light output, and lower turn-on voltages.

Mg-doped AlN/AlGaN SLs were incorporated into the DUV LED ($\lambda = 284$ nm) structures as EBL. One DUV LED was grown using Mg-doped AlN/AlGaN SL as EBL, and a second DUV LED was grown using Mg-doped AlGaN epilayer as EBL. DUV LEDs were grown by low-pressure MOCVD on c-plane sapphire substrates. Hydrogen was used as a carrier gas. The sources were trimethylgallium, trimethylaluminum, and ammonia. Prior to the epitaxial growth, the sapphire substrate was annealed at 1100 °C. A low-temperature AlN buffer layer of thickness 13 nm was initially grown at 950 °C. Then a 1.2 μm high temperature undoped AlN template was grown at 1325 °C.[20,21] A Si-doped $Al_{0.65}Ga_{0.35}N$ layer of thickness 2 μm was then grown at 1020 °C on the AlN/sapphire template, followed by a 3-period of MQW consisting of 1.5 nm thick $Al_{0.45}Ga_{0.55}N$

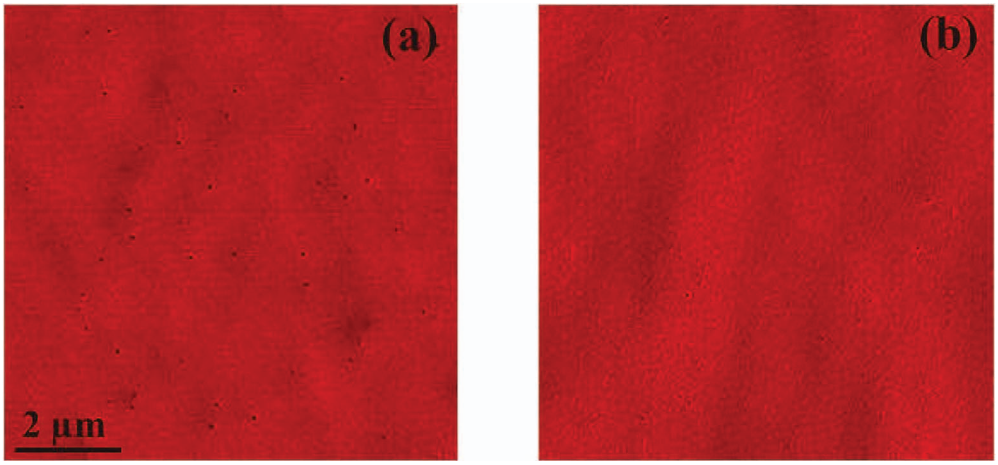

FIG. 2. The AFM images of the top surface of the DUV LED wafers with (a) Mg- AlN/AlGaN SL EBL, and (b) Mg-AlGaN EBL. The surface mean roughness of the top surface of the deep-UV LEDs were 0.3, and 0.7 nm, respectively, measured by AFM over a scan area of $10 \times 10\ \mu m^2$.

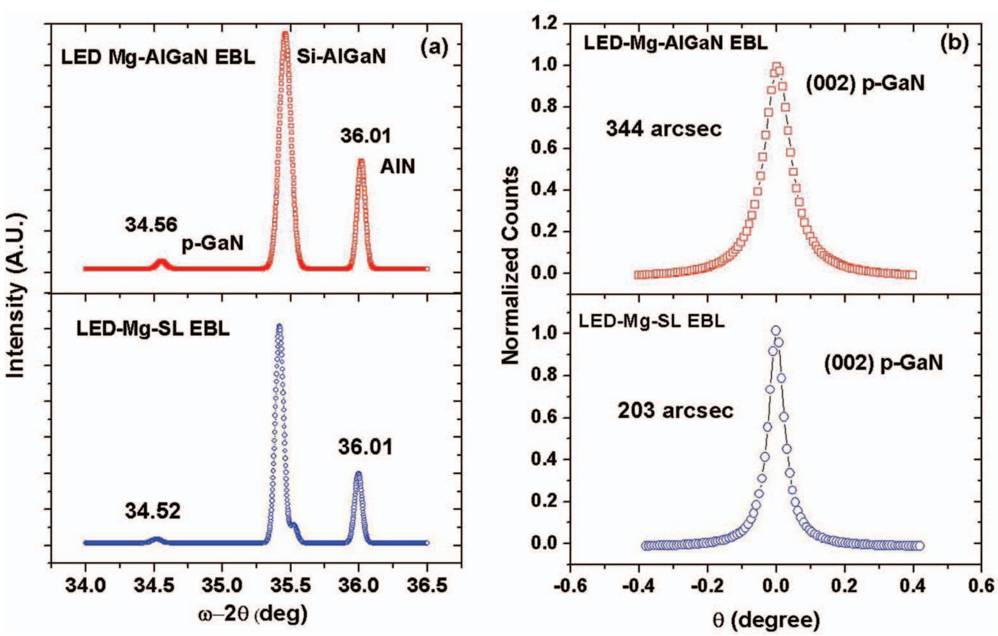

FIG. 3. (a) (0 0 2) ω–2θ scans of the DUV LEDs with Mg-AlGaN EBL (above) and Mg-SL EBL (below). (b) Rocking curves of the symmetric (002) reflection peaks in p-GaN contact layers of the DUV LEDs with Mg-AlGaN EBL (above) and Mg-SL EBL (below).

wells and 6 nm thick $Al_{0.57}Ga_{0.43}N$ barriers, then a Mg-doped AlN/$Al_{0.65}Ga_{0.35}N$ SL EBL with an average Al composition of ~0.7 was grown at a pressure of 75 Torr and a temperature of 1020 °C. SL structure consists of 15 pds. $Al_{0.65}Ga_{0.35}N$ wells are 5 nm thick and AlN barrier layers are 1 nm thick. The structure was then completed with a 25 nm thick p-$Al_{0.20}Ga_{0.80}N$ and a 200 nm thick p-GaN contact layer. For comparison, conventional DUV LED with a 20 nm Mg-doped $Al_{0.70}Ga_{0.30}N$ EBL was grown under identical growth conditions. Figure 1 shows the schematic diagrams of 284 nm DUV LED structures incorporating Mg-doped (a) AlN/AlGaN SL EBL and (b) AlGaN EBL. The electrical performances of DUV LED wafers with different device structures were characterized using wafer probing under identical conditions.

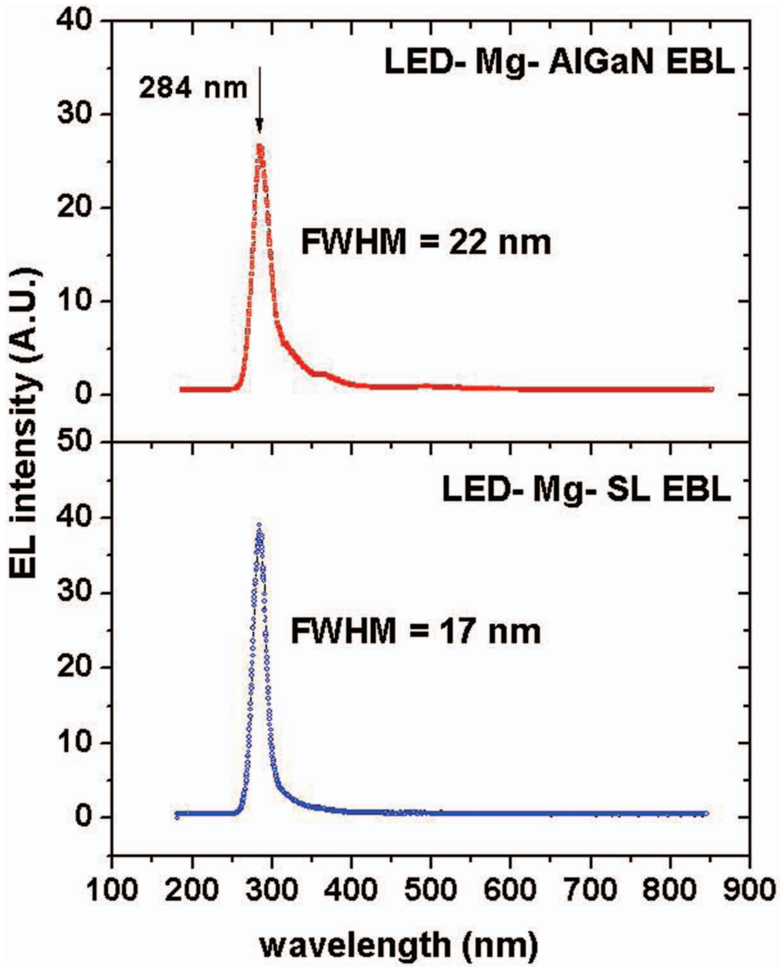

FIG. 4. Electroluminescence (EL) properties for DUV LEDs under wafer probe with Mg-AlGaN EBL, and with Mg-AlN/AlGaN SL EBL.

Figure 2 shows AFM images of top surface of two DUV LED wafers with different surface morphologies. The root mean-square (rms) surface roughness of these samples is in the range of 0.3-0.7 nm over a $10 \times 10\ \mu m^2$ scan area. The surface of LED with Mg-AlGaN EBL is characterized by high density of nanometer-scale surface pits (rms = 0.7 nm). These surface pits are associated with the surface termination of threading dislocations,[22,23] whereas the LED with Mg-AlN/AlGaN SL EBL is microscopically smooth (rms = 0.3 nm) and almost free of obvious pits. The observed difference in pits density could be attributed to the fact that the SL EBL works as a dislocation filter.[24]

Figure 3(a) shows the x-ray diffraction (XRD) (0 0 2) ω–2θ scans of the DUV LEDs with Mg-AlGaN EBL and with Mg-SL EBL. The peaks at 36.01^0 are attributed to the presence of AlN in the DUV structure. The p-GaN peak in the DUV LEDs with Mg-AlGaN EBL is at 34.56^0 and exhibits a smaller angular separation from the AlN peak than that in the DUV LED with Mg-SL EBL. This indicates that Mg-SL can reduce some of the strain in p-GaN contact layer and improves the surface morphology as seen from AFM images, which likely will result in a more uniform current injection. XRD rocking curves of the symmetric (002) reflection peak of p-GaN layers are shown in Fig. 3(b). A decreased full width at half maximum for p-GaN in DUV LED with Mg-SL, indicating a reduction in threading dislocation density in the p-GaN contact layer. This indicates that SL EBL effectively decreases threading dislocation density by working as a dislocation filter.

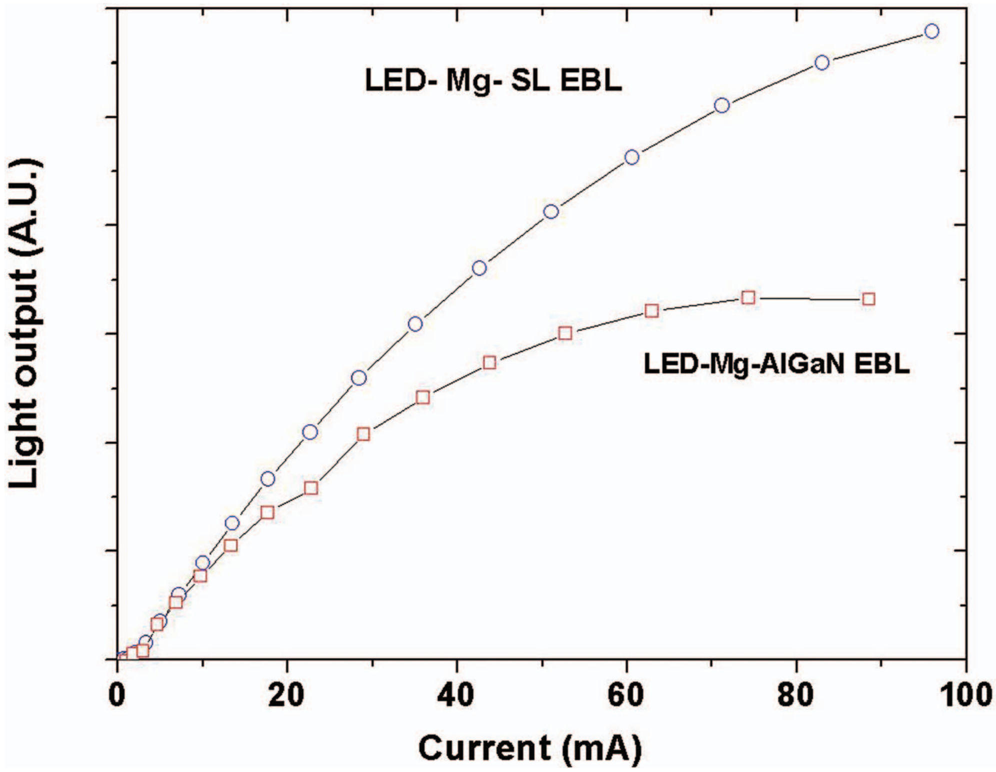

FIG. 5. Light output vs current (L-I) characteristics of DUV LEDs under wafer probe with Mg-AlGaN EBL, and with Mg-AlN/AlGaN SL EBL.

Figure 4 shows the electroluminescence (EL) emission spectra of the DUV LEDs measured under wafer probe. The EL spectra were measured at a forward current of 40 mA. The peak wavelength of both devices is around 284 nm. The EL intensity of DUV LED with Mg-SL EBL is around 30% stronger than that of DUV LED with Mg-AlGaN EBL. The full width at half maximum (FWHM) of EL spectra of DUV LEDs with Mg-AlGaN EBL, and Mg-SL EBL are 22 nm, and 17 nm, respectively.

The light emission characteristics of the DUV LEDs were estimated by comparing the intensity change with increasing current, as shown in Fig. 5. The LED with Mg-AlGaN EBL shows, in the injection current region of $I < 20$ mA, an almost linear increase in the light output. At higher injection currents, however, L-I curve shows a sublinear behavior and a tendency to saturate at $I \sim 30$ mA. At even higher currents, $I > 70$ mA, an increase in the current hardly contributes to the increase in light output, which means, only a small portion of injected carriers result in radiative recombination. The light output of the DUV LED with Mg-SL EBL is slightly higher than that of the LED with Mg-AlGaN EBL at $I \sim 10$ mA but it increases significantly with increasing injection current, showing ~40 % higher light output at $I = 80$ mA than the LED with Mg-AlGaN EBL. The light output is significantly enhanced when replacing Mg-AlGaN EBL with Mg- AlN/AlGaN SL EBL. The cause for the superiority of DUV LED with Mg-SL EBL could be the combined effect of the capability of electron cofinement and the efficiency of hole injection.[25]

The forward I-V characteristics of DUV LED wafers under wafer probe are shown in Fig. 6. The forward voltage at 20 mA for DUV LED wafer with Mg-SL EBL (7.9 V) is less than that of DUV LED with Mg-AlGaN EBL (8.4 V). The forward voltage is directly related with the p-contact resistance as well as with the uniformity of current spreading on the p-contact. The incorporation of Mg-SL EBL improves the lateral and vertical conductivity, which provides improvements in current spreading.[16,26] On the other hand, the p-GaN and contact resistance may also have been

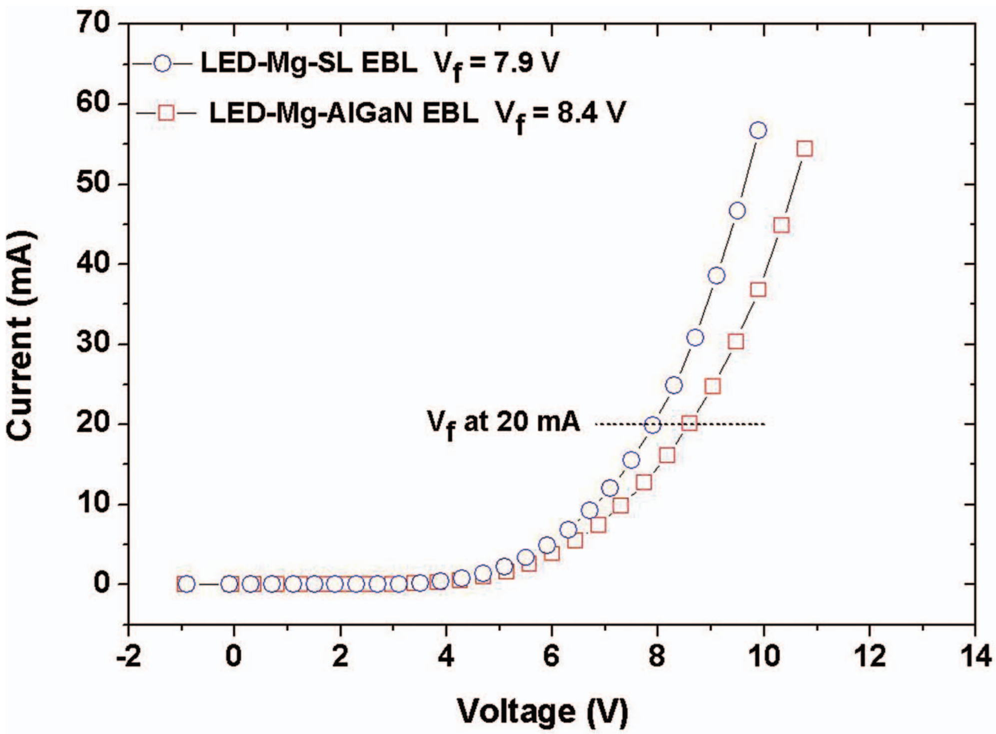

FIG. 6. Current-voltage (I – V) characteristics for DUV LEDs under wafer probe with Mg-AlGaN EBL, and with Mg-AlN/AlGaN SL EBL.

lowered, because of the improved current spreading.[27] This in turn improves the performance of these "pseudo-lateral" LEDs.

We have shown that the use of Mg-doped AlN/AlGaN SL structures as EBL in the DUV LED layer structures is an effective way to improve the performance of these LEDs. A significant enhancement of the EL intensity and light output in DUV LEDs with Mg-doped AlN/AlGaN SL EBL over similar LEDs with Mg-AlGaN EBL was demonstrated. Also, it has been shown that incorporating a Mg-doped AlN/AlGaN SL reduces the density of surface pits and improves surface morphology and crystalline quality of the p-GaN contact layer.

[1] T. M. Al Tahtamouni, N. Nepal, J. Y. Lin, H. X. Jiang, and W. W. Chow, Appl. Phys. Lett. **89**, 131922 (2006).
[2] V. Adivarahan, Q. Fareed, S. Srivastava, T. Katona, M. Gaevski, and A. Khan, Jpn. J. Appl. Phys. **46**, L537 (2007).
[3] K. B. Lee, P. J. Parbrook, T. Wang, J. Bai, F. Ranalli, R. J. Airey, and G. Hill, J. Cryst. Growth **311**, 2857 (2009).
[4] A. Chitnis, J. P. Zhang, V. Adivarahan, M. Shatalov, S. Wu, R. Pachipulusu, V. Mandavilli, and M. A. Khan, Appl. Phys. Lett. **82**, 2565 (2003).
[5] A. J. Fischer, A. A. Allerman, M. H. Crawford, K. H. A. Bogart, S. R. Lee, R. J. Kaplar, W. W. Chow, S. R. Kurtz, K. W. Fullmer, and J. J. Figiel, Appl. Phys. Lett. **84**, 3394 (2004).
[6] J. Park, D. W. Fothergill, X. Zhang, Z. J. Reitmeier, J. F. Muth, and R. F. Davis, Jpn. J. Appl. Phys. **44**, 7254 (2005).
[7] A. Yasan, R. McClintock, K. Mayes, D. Shiell, L. Gautero, S. R. Darvish, P. Kung, and M. Razeghi, Appl. Phys. Lett. **83**, 4701 (2003).
[8] A. Hanlon, P. M. Pattison, J. F. Kaeding, R. Sharma, P. Fini, and S. Nakamura, Jpn. J. Appl. Phys., Part 2 **42**, L628 (2003).
[9] M. L. Nakarmi, K. H. Kim, M. Khizar, Z. Y. Fan, J. Y. Lin, and H. X. Jiang, Appl. Phys. Lett. **86**, 092108 (2005).
[10] A. Saxler, W. C. Mitchel, P. Kung, and M. Razeghi, Appl. Phys. Lett. **74**, 2023 (1999).
[11] V. Adivarahan, S. Wu, J. P. Zhang, A. Chitnis, M. Shatalov, V. Mandavilli, R. Gaska, and M. Asif Khan, Appl. Phys. Lett. **84**, 4762 (2004).
[12] K. Kumakura and N. Kobayashi, Jpn. J. Appl. Phys. **38**, L1012 (1999).
[13] I. D. Geophert, E. F. Schubert, A. Osinsky, and P. E. Norris, Electron. Lett. **24**, 1109 (1999).
[14] P. Kozodoy, M. Hansen, S. P. DenBaars, and U. K. Mishra, Appl. Phys. Lett. **74**, 3681 (1999).
[15] E. F. Schubert, W. Grieshaber, and I. D. Goepfert, Appl. Phys. Lett. **69**, 3737 (1996).
[16] B. Cheng, S. Choi, J. E. Northrup, Z. Yang, C. Knollenberg, M. Teepe, T. Wunderer, C. L. Chua, and N. M. Johnson, Appl. Phys. Lett. **102**, 231106 (2013).

[17] C. H. Jang, J. K. Sheu, C. M. Tsai, S. C. Shei, W. C. Lai, and S. J. Chang, IEEE Photon. Technol. Lett. **20**(13), 1142 (2008).
[18] S. Nakamura, M. Senoh, S. Nagahama, N. Iwasa, T. Yamada, T. Matsushita, H. Kiyoku, Y. Sugimoto, T. Kozaki, H. Umemoto, M. Sano, and K. Chocho, Jpn. J. Appl. Phys. **35**, L1568 (1997).
[19] A. A. Allerman, M. H. Crawford, M. A. Miller, and S. R. Lee, J. Cryst. Growth **312**, 756 (2010).
[20] T. M. Al Tahtamouni, J. Li, J. Y. Lin, and H. X. Jiang, J. Phys. D: Appl. Phys. **45**, 285103 (2012).
[21] T. M. Al Tahtamouni, J. Y. Lin, and H. X. Jiang, Appl. Phys. Lett. **101**, 192106 (2012).
[22] P. Cantu, F. Wu, P. Waltereit, S. Keller, A. E. Romanov, U. K. Mishra, S. P. DenBaars, and J. S. Speck, Appl. Phys. Lett. **83**, 674 (2003).
[23] T. M. Al Tahtamouni, A. Sedhain, J. Y. Lin, and H. X. Jiang, Appl. Phys. Lett. **92**, 092105 (2008).
[24] Hong-Mei Wang, Jian-Ping Zhang, Chang-Qing Chen, Q. Fareed, Jin-Wei Yang, and M. Asif Khan, Appl. Phys. Lett. **81**, 604 (2002).
[25] T. Kolbe, F. Mehnke, M. Guttmann, C. Kuhn, J. Rass, T. Wernicke, and M. Kneissl, Appl. Phys. Lett. **103**, 031109 (2013).
[26] A. Kinoshita, H. Hirayama, M. Ainoya, Y. Aoyagi, and A. Hirata, Appl. Phys. Lett. **77**, 175 (2000).
[27] J. K. Sheu, G. C. Chi, and M. J. Jou, IEEE Electron Device. Lett **22**, 160 (2001).