Extraction efficiency simulation in deep ultraviolet AlGaN light emitting diodes

Qian Fan1 · Xianfeng Ni1 · Bin Hua1 · Xing Gu1

Received: 30 June 2020 / Accepted: 8 June 2021 / Published online: 14 July 2021
© The Author(s), under exclusive licence to Springer Science+Business Media, LLC, part of Springer Nature 2021

Abstract
A ray tracing model is developed to study the light extraction efficiency (LEE) of the nitride wide band gap semiconductor deep ultraviolet light emitting diodes (DUV-LEDs). The basic device structure is flip-chip LED device with dome shape encapsulation. Various device parameters such as reflecting p-metal, absorption coefficient of the AlN layer, sapphire surface roughness etc have been examined. We have found that the transparency of the AlGaN/AlN epitaxial layers as well as the encapsulation material play key roles in improving the LEE and spatial intensity distribution. To verify the transparency of the epi-layers, highly doped n-type Al0.61Ga0.39N on AlN template are grown on sapphire substrate by high-temperature metalorganic chemical vapor deposition (HT-MOCVD), then the crystal and optical properties are measured and analyzed. The calculated the absorption coefficient of the AlN is below 10^3 cm^-1, which paves the way to achieve high extraction efficiency DUV LEDs.

Keywords DUV LEDs · Light extraction efficiency · Ray tracing · AlGaN

1 Introduction
Deep ultraviolet light emitting diodes, especially in the wavelength range of 260–290 nm, are gaining significant attentions for research and development activities in various applications such as water purification, surface disinfection, and pharmaceutical production. Wideband gap nitride semiconductor namely the AlGaN based multiple quantum wells (MQWs) structure in no doubt is the best candidate in achieving such short wavelength emission. Similar to nitride semiconductor LEDs in visible light spectrum range, typical DUV structures are epitaxially grown on c-plane sapphire substrate starting from thick AlN template, high Al mole-fraction n-type AlGaN current spreading layer, un-doped AlGaN MQWs, and p-type AlGaN followed with thin heavily doped p-type GaN contact layer, by MOCVD method (Khan et al. 2005; Yan et al. 2015). Unlike the InGaN MQWs, in which microstructural features like V-pits help to prevent carriers from reaching non-radiative...
recombination centers so that high emission efficiency (Yong et al. 2007; Tomiya et al. 2011) can be obtained, DUV LEDs are much more sensitive to the presence of the epitaxial defects such as threading dislocations (Lee et al. 2005; Shatalov et al. 2012). On the homogeneous AlN single crystal substrates with much less defects, the internal quantum efficiency (IQE) of the DUV LEDs is reported to reach as high as 70% (Grandusky et al. 2011). However, the high price and low yield of such substrate makes it hard to become popular. The AlGaN/AlN epi-layers grown on regular sapphire substrate is currently still the mainstream solution, and thus is the focus of our study.

On the other hand, device structure and fabrication processes also play important roles in improving the light extraction efficiency. For instance, the p-GaN cap layer is believed to reduce the turn-on voltage but strongly absorb DUV due to its narrower band gap. Therefore, the thickness of the top p-GaN is a tradeoff between lower contact resistance and less optical loss. Flip-chip LED structure is often used in DUV LEDs (Hwang et al. 2011), where p-contact metal has large contact area to reflect the emitted light towards substrate direction. The choosing of p-contact metal is then critical, since most of the metals are UV absorbing. Other factors, like surface roughening, encapsulation, and substrate removal etc., all affect the external quantum efficiency (EQE) of the device. They need more careful optimization compared with regular visible light LEDs. So far, the reported highest EQE of DUV LEDs can barely reach 20% with total radiated power of 100 mW (Inoue et al. 2015).

In this study, we utilize ray tracing (RT) technique to analyze the dependence of light extraction behavior on various device parameters including reflection metal, existence of encapsulation layer, and the surface roughness. We developed two-dimensional simulator to solve the electromagnetic wave continuity equations in absorbing media with certain boundary conditions. Earlier reports of RT modeling on visible spectrum LEDs (Yong et al. 2007; Tomiya et al. 2011) can hardly be applied to DUV regime since the drastic difference in device structure. In particular, the absorption coefficient of the AlN and its alloys in DUV range is very essential to theoretical calculation but literature-inconsistent. The reported absorption coefficient of AlN thin film, which strongly depends on the deposition techniques, defects density and crystal orientations, could vary from $10^2$ to $10^4$ cm$^{-1}$ (Demiryont et al. 1986; Zarwasch et al. 1992; Lu et al. 2008; Yan et al. 2014). It will result in significant difference in device performance as shown in our simulation. In order to obtain an accurate estimation, AlN grown by MOCVD at the temperature above 1300°C on sapphire substrate is measured in spectrophotometer at normal incident angle. The fitted transmittance shows that the HT deposited nitride thin film has low enough absorption coefficient to achieve good light extraction in DUV LEDs.

## 2 Modeling

The baseline flip-chip device structure used in this study is shown in Fig. 1 with reflective p-contact metal laying on the very bottom. To reduce the turn-on voltage, p-GaN cap layer above the metal is thin (10 nm) enough to reduce absorption as much as possible. We assume the n-contact towards n-AlGaN current spreading layer is done through n-via process that occupies negligible surface area. Above the cap layer, 200 nm p-AlGaN, 50 nm AlGaN/AlN MQWs, and 2000 nm n-AlGaN are stacked in sequence with Al% set to be 60%. All these device layers are grown on 3000 nm thick AlN template on regular single side polished sapphire substrate, which are shown in Fig. 1 as the top two layers within the encapsulation. Although nano-pattern sapphire substrate (NPSS) is reported to enhance
the crystal qualities during AlN template growth (Dong et al. 2014), we didn’t take it into account because those wavelength-comparable sized patterns and consequently the lateral overgrowth induced hollow cavities at AlN/sapphire interface will bring in complicated scattering effects that need electromagnetic wave simulation and make the RT calculation almost impossible.

Also we assume the sapphire substrate is thinned down to 50 μm. Usually the after-lapping, sapphire surface roughness ranges from 0.5 to 2 μm, which is much larger than the wavelength of DUV. Quite some theoretical calculations were done to study the scattering effects on the rough surface by solving Maxwell’s equations to predict the propagation of light waves (Aurelien 2013; Windisch et al. 2002). It shows that both the reflection and the refraction light should be treated with diffusive and specular components. Usually, those numerical calculations can hardly be implemented in RT models due to heavy computational complexity. Instead, empirical models based on bidirectional scattering distribute function (BSDF) to describe rough surface consists of microfacets are widely adopted in RT calculations. They have been intensively studied by Phong, C-T, O-N and GCX (Phong 1975; Cook and Torrance 1982; Oren and Nayar 1994; Bruce et al. 2007), and successfully applied in the area such as computer image/graphic rendering. As illustrated in Fig. 2a, we here assume the reflection and refraction light scattered at the rough interface follows Gaussian distribution, and the surface microfacets distribution follows Beckmann function (Eq. 1), where $\theta_m$ is the angle between incoming ray and marco-surface normal direction.

$$D = \frac{1}{\pi a^2} \cos^4 \theta_m \exp \left( -\frac{\tan^2 \theta_m}{a^2} \right)$$

Take refraction light for example, Fig. 2b shows calculated transmittance function (solid line). The dashed lines represented the angular distribution of the transmittance for the light rays at 10-, 30- and 50-degree incident angle. For simplicity, we consider the diffusive lights from surface scattering as the second light source with limited angular sampling, and omit any re-entrance back into sapphire bulk.

Encapsulation packaging between device and air is very useful in LEDs industry to improve light extraction efficiency. On the other hand, DUV transparent encapsulation material is not mature yet because of the absorption from organic compounds. Quartz or sapphire based inorganic encapsulation although has no worry on transparency, but its poor resistance to air moisture and difficulties in processing are still main obstacles. Alternatively, DUV transparent organic compounds such as methyl-siloxane,
fluorinated resin (Bae et al. 2015; Hirano et al. 2016) are compatible with current LEDs process. In our baseline structure, we still assume a 250 μm thick (radius) dome shape encapsulation is applied.

Most of the metals participating in good ohmic contact formation in regular LEDs process are not suitable in DUV spectrum range due to strong absorption. The possible candidates are Al, W, Rh (Weaver et al. 1977; Werner et al. 2009; Rakić 1995), but there are no experimental evidences showing that they alone could produce reasonably low contact resistance to p-GaN. Therefore, thin Ni(2 nm) is laid first as contact layer, then caped with those reflecting metal, together to form the p-contact. Three cases namely Ni/W, Ni/Rh and Ni/Al are examined and compared. The calculated s-polarization and p-polarization reflectance on those bi-layer stacks are plotted in Fig. 3. Theoretically Al could provide highest reflectance in DUV, therefore Ni/Al stack is considered as the baseline option. In all, the main device parameters used in this modeling are summarized in Table 1, noting that the optical properties are given at 280 nm wavelength.
Table 1  LED device parameters used in this study, where d denotes for layer thickness, W is the device width and R is the radius of the encapsulation, n, k, α are refraction index, extinction and absorption coefficient respectively at 280 nm wavelength.

| Layers       | Parameters                                         |
|--------------|----------------------------------------------------|
| p-metal      | W = 200 μm, Ni = 2 nm, n = 2.02, k = 2.24          |
| p-GaN cap    | d = 5 nm, α = 1.6e + 5 cm⁻¹, n = 2.58              |
| p-AlGaN      | d = 200 nm, Al% = 60%, α = 1.0e+3 cm⁻¹, n = 2.29   |
| MQWs         | d = 50 nm, α = 1.0e+3 cm⁻¹                         |
| n-AlGaN      | d = 2000 nm, Al% = 60%, α = 1.0e+2 cm⁻¹, n = 2.29  |
| AlN buffer   | d = 3000 nm, α = 1.0e+2 cm⁻¹, n = 2.1              |
| Sapphire     | d = 50 μm, n = 1.82, αₙ = 0.6                      |
| Encapsulation| R = 250 μm, n = 1.45, αₙ = 1.0e+1 cm⁻¹             |

Fig. 3  Calculated s-polarized and p-polarized incident light (at 280 nm) reflectance on Ni/Al, Ni/W and Ni/Rh metal stacks, with Ni thickness is 2 nm.

3 Results and discussions

Figure 4a shows the distribution of the light rays plot from: baseline structure; baseline without encapsulation; baseline without encapsulation plus the sapphire top surface is ideally smooth. The simulation is assuming the light rays originated from the MQWs are identical towards every direction. As we can see the trapping of the light rays inside the chip especially in nitride films is still obvious. In ideal cubic geometry, most of the light will be reflected back and forth between interfaces. The dome shape encapsulation on the other hand could help light rays reaching its boundary to get extracted. Since many materials are lossy in this structure, usually after approximately 10 times bouncing between interfaces, the rays will vanish (below 10% of the original intensity). The rough surface of top sapphire acts as diffuser to randomize the propagation. Here the LEE is defined as the intensity ratio between output rays traveling into air and the rays generated in the MQWs, and value comes out to be 35.5% for the baseline structure. Figure 4b shows the angular intensity distribution for the LEDs in all these three configurations. The dome shape encapsulation significantly improves the extraction of the light by widening the emission range from ± 60° to almost ± 90. The existence of the surface roughness, on the other hand, helps to make the distribution within emission angle more uniform.

Table 2 listed the calculated LEE of the devices with various configurations at 280 nm wavelength. Encapsulation is the most effective way to reduce the TIR effect and get more...
Fig. 4  
(a) Light ray plot for the UV LED with dome shape encapsulation.  
(b) Angular light intensity distribution for the UV LED in different configurations (with or without sapphire roughening, with or without encapsulation)
lights out of the chip, as the LEE increases more than 10% from the one without encapsulation. Top surface roughness is the second biggest factor on improvement. Compared with the reports on conventional visible light LEDs (Huang et al. 2006), this increment is not that significant. Possible reasons may include the absorption from the p-contact; ideally smooth chip edge; and non-lambertian scattering from sapphire surface. Different p-metal stack, on the other hand, has small influence (less than 2%) on the LEE compared to the baseline device structure. Obviously, if highly absorbing p-GaN is eliminated from the LEDs, significant improvement can be expected.

We found the absorption coefficient of the AlGaN/AlN epi-layers and the encapsulation material, plays important role in determine the output ray intensity. For instance, the LEE of the baseline structure drops approximately 4% if the absorption coefficient of the AlN increase from $10^2$ to $10^3$ cm$^{-1}$, and the efficiency will reduce down to single digit if the coefficient reaches $10^4$ cm$^{-1}$. The encapsulation’s absorption has even greater impact, due to much larger traveling distance before the rays leave it. The relationship between LEE and encapsulation thickness (dome radius) under different absorption coefficients is plotted in Fig. 5. As we calculated, the threshold values for absorption coefficient (at 250 μm thickness) and thickness (at 10 cm$^{-1}$ absorption coefficient) of the encapsulation are 23 cm$^{-1}$ and 491.8 μm respectively, which means the LEE will benefit no more from encapsulation if its absorption or thickness is greater than that number.

One important phenomenon observed on nitride LEDs is the polarized emission. It is found that the in-plane (c-plane) light emitted from AlGaN based MQWs switches its polarization characteristic from transverse electric (TE) to transverse magnetic (TM) mode at some critical Aluminum composition (Banal et al. 2009). Such transition is caused by the strong build-in stain that could split the valance band of the nitride into heavy hole and split-off hole sub-bands (Taniyasu and Kasu 2011). If the lowest energy excitation in MQWs is a heavy hole, then TE polarization is obtained, otherwise it will be TM mode.

### Table 2
Calculated LEE with various DUV LED configurations at 280 nm wavelength

| Configurations                      | LEE (%) |
|-------------------------------------|---------|
| Baseline structure (p-metal is NiAl)| 35.5    |
| Baseline but without encapsulation  | 22.9    |
| No encapsulation, smooth sapphire   | 19.1    |
| Baseline but p-metal is NiRh        | 34.9    |
| Baseline but p-metal is NiW         | 35.1    |

![Fig. 5](image-url) The dependency of LEE on the radius of dome encapsulation, with different absorption coefficients.

![Diagram](image-url)
The degree of the polarization, defined as \( P = (I_{TE} + I_{TM})/(I_{TE} + I_{TM}) \), for 280 nm DUV LEDs is reported around \(-0.1\) if grown on sapphire substrate (Northrup et al. 2012). Hereby, we also take polarization into account in our modeling. The LEE calculated in Table 2 is assuming zero degree of polarization. While in case of TM polarized emission \((P = -0.1)\), the LEE drops slightly by 1.4% which is not as significantly as other literature (Nam et al. 2004). The RT model presented here assumes the degree of elliptic polarization from MQWs emission has uniform spatial distribution along every direction. If the emission from the MQWs can be restored to TE mode, then the performance of the device can be improved. The fine tune on barrier Al composition and film stress could be the way to achieve it.

To evaluate the properties of the high Al-content nitride epi-layer, we specially optimize the growth conditions of AlGaN and AlN films on planar 2-in. sapphire substrate using high temperature (over 1300C) MOCVD tool. Trimethylaluminum (TMAl) and NH₃ are Al and N sources respectively. High quality crack-free thick AlN film was obtained after optimizing the growth conditions. The thickness non-uniformity of 3μm thick AlN template is below 2%, with 157 and 358 arcsec full width half maximum (FWHM) on (002) and (102) orientations measured in X-ray diffraction (XRD) shown in Fig. 6. Highly doped n-type AlGaN film deposited on such AlN template was also achieved, with Al mole fraction reaching 61% by XRD. The sheet resistance of the n-AlGaN film reaches 1370 Ω/□ identified by room temperature hall measurement. The wafer warpage of the 2 in. sapphire is below 20μm indicating a good stress control during the growth.

The transparency of our HT MOCVD grown AlN on double side deposited sapphire is studied. The transmittance of the film is measured in LAMBDA 750 UV-NIR spectrophotometer. The solid line in Fig. 7 is the transmittance of this sample in the wavelength from 200 to 550 nm with normal incidence. The interference oscillations in visible light spectrum range helps to identify the film thickness. We assume the absorption coefficient of the MOCVD grown AlN follows exponential distribution (Xuantong et al. 1990) over the wavelength as following

\[
\alpha = A \cdot \exp(B \cdot \lambda)
\]

where A and B are the factors to be fitted. The coefficient of the AlN is then calculated to be \(10^{2.2}\) cm\(^{-1}\), and the simulated transmittance is plotted in dotted line in Fig. 7 which matches well with the measurement. Experimentally, we are now running epi-condition optimizations for the active region within DUV LEDs. For further improvement on light extraction, TE polarized emission study and the optical properties of the fluorine resin encapsulation are our main focus.

4 Conclusions

Ray tracing modeling is applied to the high Al% concentration nitride semiconductor LEDs aiming on 280 nm wavelength emission. The baseline device structure used in this study has flip chip configuration with high reflective NiAl p-metal contact; thin p-GaN contact layer; roughened top sapphire surface and dome shape low loss encapsulation material. We found
the light extraction efficiency could reach 35.5% with spatial distribution covers nearly entire upper sphere. As comparison, without encapsulation, the efficiency drops more than 10% and the emission angle narrows to ± 60°. Surface roughness also helps in enhancing LEE and uniformly distributing the light. Due to the existence of the absorbing p-GaN, different p-metal stacks bring less influence on LEE. Absorption coefficients of both nitride semiconductor and encapsulation play important roles. To achieve reasonably good LEE, the absorption coefficients of nitride and encapsulation should be kept below 10^{-3} and 20 cm^{-1} respectively. Furthermore, high temperature AlN and $n$-Al$_{0.6}$Ga$_{0.39}$N films are epitaxially deposited on planar sapphire substrate and evaluated with XRD, Hall and spectrophotometer measurements. The fitting shows the absorption coefficient of our MOCVD deposited nitride film is around 10^{-2.2} cm^{-1} at 280 nm wavelength which is suitable the DUV LEDs process.

Fig. 6  

(a) Thickness mapping showing thick (> 3 μm) uniform AlN template layer grown on 2 inch planar c-sapphire.  
(b) (002) FWHM: 157arcsec  
(c) (102) FWHM: 358arcsec
Acknowledgements
The authors from Southeast University would like to thank the research funding from Suzhou Industrial Park District (Funding Number 7760890012).

References

Aurelien, D.: Surface-roughened light-emitting diodes: an accurate model. J. Display Technol. 9(5), 301–316 (2013)
Bae, J., Kim, Y.H., Kim, H.Y., Kim, Y.B., Jin, J.: Ultraviolet light stable and transparent sol-gel methyl siloxane hybrid material for UV light-emitting diode (UV LED) encapsulant. ACS Appl. Mater. Interfaces 7, 1035–1039 (2015)
Banal, R.G., Funato, M., Kawakami, Y.: Optical anisotropy in [0001]-oriented Al$_x$Ga$_{1-x}$N/AlN quantum wells (x>0.69). Phys. Rev. B 79, 121308 (2009)
Bruce, W., Stephen, R.M., Hongsong, L., Kenneth, E.T.: Microfacet models for refraction through rough surfaces. In: Euro-Graphics Symposium on Rendering EGSR’07, pp. 195–206 (2007)
Cook, R., Torrance, K.: A Reflectance Model for Computer Graphics. ACM Trans. Gr. 1, 7–24 (1982)
Demiryont, H., Thompson, L.R., Collins, G.J.: Optical properties of aluminum oxynitrides deposited by laser-assisted CVD. Appl. Opt. 25, 1311–1318 (1986)
Dong, P., Yan, J., Zhang, Y., Wang, J., Zeng, J., Geng, C., Cong, P., Sun, L., Wei, T., Zhao, L., Yan, Q., He, C., Qin, Z.: AlGaN-based deep ultraviolet light-emitting diodes grown on nano-patterned sapphire substrates with significant improvement in internal quantum efficiency. J. Cryst. Growth 395, 9–13 (2014)
Grandusky, J.R., Gibb, S.R., Mendrick, M.C., Moe, C., Wraback, M., Schowalter, L.J.: High output power from 260 nm pseudomorphic ultraviolet light-emitting diodes with improved thermal performance. Appl. Phys. Express 4, 082101 (2011)
Hirano, A., Nagasawa, Y., Ippomatsu, M., Aosaki, K., Honda, Y., Amano, H., Akasaki, I.: Development of AlGaN-based deep-ultraviolet (DUV) LEDs focusing on the fluorine resin encapsulation and the prospect of the practical applications. Proceedings of SPIE, 9926, 99260 (2016)
Huang, S.-H., Hornig, R.-H., Wen, K.-S., Lin, Y.-F., Yen, K.-W., Wuu, D.-S.: Improved light extraction of nitride-based flip-chip light-emitting diodes via sapphire shaping and texturing. IEEE Photon. Technol. Lett. 18(24), 2623–2625 (2006)
Extraction efficiency simulation in deep ultraviolet AlGaN…

Hwang, S., Morgan, D., Kesler, A., Lachab, M., Zhang, B., Heidari, A., Nazir, H., Ahmad, I., Dion, J., Fareed, Q.: 276 nm substrate-free flip-chip AlGaN light-emitting diodes. Appl. Phys. Express 4, 032102 (2011)

Inoue, S.-I., Naoki, T., Kinoshita, T., Obata, T., Yanagi, H.: Light extraction enhancement of 265 nm deep-ultraviolet light-emitting diodes with over 90 mW output power. Appl. Phys. Lett. 106, 131104 (2015)

Khan, M.A., Shatalov, M., Maruska, H.P., Wang, H.M., Kuokstis, E.: III-nitride UV devices. Jpn. J. Appl. Phys. 44, 7191–7206 (2005)

Lee, Y.J., Hsu, T.C., Kuo, H.C., Wang, S.C., Yang, Y.L., Yen, S.N., Chu, Y.T., Shen, Y.J., Hsieh, M.H., Jou, M.J., Lee, B.J.: Improvement in light-output efficiency of near-ultraviolet InGaN-GaN LEDs fabricated on stripe patterned sapphire substrates. Mater. Sci. Eng. B 122, 184–187 (2005)

Lu, P., Collazo, R., Dalmau, R.F., Durkaya, G., Dietz, N., Sitar, Z.: Different optical absorption edges in AlN bulk crystals grown in m- and c-orientations. Appl. Phys. Lett. 93, 131922 (2008)

Nam, K.B., Li, J., Nakarmi, M.L., Lin, J.Y., Jiang, H.X.: Unique optical properties of AlGaN alloys and related ultraviolet emitters. Appl. Phys. Lett. 84, 5264–5266 (2004)

Northrup, J.E., Chua, C.L., Yang, Z., Wunderer, T., Kneissl, M., Johnson, N.M., Kolbe, T.: Effect of strain and barrier composition on the polarization of light emission from AlGaN/AlN quantum wells. Appl. Phys. Lett. 100, 021101 (2012)

Oren, M., Nayar, S.: Generalization of Lambert’s reflectance model. In: SIGGRAPH’94 Proceedings, pp. 239–246 (1994)

Phong, B.T.: Illumination for computer generated pictures. In: Conference Proceedings, vol. 6, pp. 311–317. ACM Press (1975)

Rakić, A.D.: Algorithm for the determination of intrinsic optical constants of metal films: application to aluminum. Appl. Opt. 34, 4755–4767 (1995)

Shatalov, M., Sun, W., Lunev, A., Xuhong, H., Dobrinsky, A., Bilenko, Y., Yang, J., Shur, M., Gaska, R., Moe, C., Garrett, G., Wraback, M.: AlGaN Deep-Ultraviolet Light-Emitting Diodes with External Quantum Efficiency above 10%. Appl. Phys. Express 5, 082101 (2012)

Taniyasu, Y., Kasu, M.: Polarization property of deep-ultraviolet light emission from C-plane AlN/GaN short-period superlattices. Appl. Phys. Lett. 99, 251112 (2011)

Tomiya, S., Kanitani, Y., Tanaka, S., Okubo, T., Hono, K.: Atomic scale characterization of GaInN/GaN multiple quantum wells in V-shaped pits. Appl. Phys. Lett. 98, 181904 (2011)

Weaver, J.H., Olson, C.G., Lynch, D.W.: Optical investigation of the electronic structure of bulk Rh and Ir. Phys. Rev. B 15, 4115–4118 (1977)

Werner, W.S.M., Glantschnig, K., Ambrosch-Draxl, C.: Optical constants and inelastic electron-scattering data for 17 elemental metals. J. Chem. Phys. Ref. 38, 1013–1092 (2009)

Windisch, R., Rooman, C., Dutta, B., Knobloch, A., Borghs, G., Dohler, G.H., Heremans, P.: Light-extraction mechanisms in high-efficiency surface-textured light-emitting diodes. Top. Quantum Electron. 8(2), 248–255 (2002)

Yan, Q., Janotti, A., Scheffler, M., VanWeve, C.G.: Origins of optical absorption and emission lines in AlN. Appl. Phys. Lett. 105, 111104 (2014)

Yan, J., Wang, J., Zhang, Y., Cong, P., Sun, L., Tian, Y., Zhao, C., Li, J.: AlGaN-based deep-ultraviolet light-emitting diodes grown on high-quality AlN template using MOVPE. J. Cryst. Growth 344, 254–257 (2015)

Ying, X., Feldman, A., Farabaugh, E.N.: Fitting of transmission data for determining the optical constants and thicknesses of optical films. J. Appl. Phys. 67, 2056–2059 (1990)

Yong, A.M., Soh, C.B., Zhang, X.H., Chow, S.Y., Chua, S.J.: Investigation of V-defects formation in InGaN/GaN multiple quantum wells grown on sapphire. Thin Solid Films 515, 4496–4500 (2007)

Zarwasch, R., Rille, E., Pulker, H.K.: Fundamental optical absorption edge of reactively direct current magnetron sputter-deposited AlN thin films. J. Appl. Phys. 71, 5275–5277 (1992)

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.