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Enhancing the light extraction of AlGaN-based ultraviolet light-emitting diodes in the nanoscale

Yanan Guo,[a,b,c,d,†] **Jianchang Yan,**[a,b,c,d,*,†] **Yun Zhang,**[a,b,c,d]
Junxi Wang,[a,b,c,d,*] **and Jinmin Li**[a,b,c,d]

[a]Chinese Academy of Sciences, Institute of Semiconductors, Research and Development Center for Solid State Lighting, Haidian District, Beijing, China
[b]University of Chinese Academy of Sciences, Shijingshan District, Beijing, China
[c]Beijing Engineering Research Center for the Third-Generation Semiconductor Materials and Application, Haidian District, Beijing, China
[d]State Key Laboratory of Solid State Lighting, Haidian District, Beijing, China

Abstract. AlGaN-based ultraviolet light-emitting diodes (UV LEDs) are promising next-generation UV sources for a wide variety of applications. The state-of-the-art AlGaN-based UV LEDs exhibit much lower output power and external quantum efficiency than highly commercialized GaN visible LEDs. One key issue for UV LEDs is the poor light-extraction efficiency. We have reviewed the recent progress in the light extraction approaches for AlGaN-based UV LEDs, including the highly reflective techniques, and the surface/interface modification for total internal reflection mitigating. Moreover, AlGaN-based UV LEDs in the nanoscale structures, such as nanopillar, nanorod, and nanowire structures, are also discussed. © *2018 Society of Photo-Optical Instrumentation Engineers (SPIE)* [DOI: 10.1117/1.JNP.12.043510]

Keywords: AlGaN; ultraviolet light-emitting diodes; light-extraction efficiency.

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1 Introduction

AlGaN-based ultraviolet light-emitting diodes (UV LEDs) have emerged as the most promising UV sources to replace the traditional mercury lamps, due to their advantages such as compact size, low operation voltage, long lifetime, and environmental friendliness. Since the first AlGaN/GaN quantum well p–n diode with band-to-band recombination emission wavelength at 353.6 nm (shorter than the GaN bandgap wavelength) reported in 1998,[1] many research groups have made great efforts to develop AlGaN-based UV LEDs with shorter wavelength and higher output power; several companies have started to commercialize UV LED devices.[2–5] Recently, Takano et al.[6] claimed to obtain deep-UV (DUV) LEDs with a maximum external quantum efficiency (EQE) of 20.3% at 275 nm. Inoue et al.[7] reported a 265-nm single-chip LED with a record continuous-wave output power in excess of 150 mW (corresponding EQE: 3.9%) for an injection current of 850 mA. However, the typical EQE of DUV LEDs is still in the single-digit percentage range and the output power in a couple of milliwatts, depending on the wavelength. These values are much lower than that obtained in highly commercialized GaN visible LEDs.

The low light-extraction efficiency (LEE) of AlGaN-based UV LEDs is one major bottleneck limiting the EQE. Due to the insufficient hole concentration in Al-rich p-AlGaN layer, AlGaN-based UV LEDs generally use p-GaN layer on the top of the structure to achieve hole accumulation[8–11] and ohmic contact. But the p-GaN layer would strongly absorb UV light.[12] Such optical loss in the p-side can be drastically reduced when the p-GaN layer is thinned,[13] partially removed,[14,15] or replaced with a transparent AlGaN or AlGaN/AlGaN short period

*Address all correspondence to: Jianchang Yan, E-mail: yanjc@semi.ac.cn; Junxi Wang, E-mail: jxwang@semi.ac.cn

[†]Yanan Guo and Jianchang Yan contributed equally to this work.

superlattices (SPSLs) associated with highly reflective metallization stack.[16,17] Furthermore, serious total internal reflection (TIR) occurs at the epitaxial layers/substrate interface and substrate/air interface because of the large difference in refraction indices. A large amount of photons are trapped inside the LED structure and finally absorbed after multiple internal reflections. Disturbing the TIR at the interfaces would be beneficial to achieve high-efficient UV LEDs. In addition, the intrinsic anisotropic optical polarization properties of AlGaN material also affect the LEE significantly. In c-plane AlGaN-active region, light can be emitted as either transverse-electric (TE, electrical field $\vec{E} \perp c-\text{axis}$) polarized mode or transverse-magnetic (TM, $\vec{E} \| c-\text{axis}$) polarized mode, and the predominant emission mode depends on the topmost valence subbands. The TE-polarized light mainly propagates in the vertical direction, whereas the TM-polarized light mainly propagates in the lateral direction and suffers severer TIR than the TE-polarized light. Ryu's simulation indicated that LEE of TM mode is more than 10 times smaller than that of TE mode in flip-chip DUV LEDs.[12] Thus, it is necessary to develop approaches to enhance the LEE of TM-mode[18–21] or promote the emission intensity of TE-mode relative to TM-mode by adjusting the order of valence subbands in AlGaN, for example, adopting (Al)GaN-delta quantum wells,[22,23] GaN/AlN quantum dot heterostructure,[24] and asymmetric ultrathin $(\text{GaN})_m/(\text{AlN})_n$ ($m \leq 2$) superlattice (SPSL).[25] Table 1 summarizes the current prevailing techniques for UV light extraction developed by various groups.

In this paper, we focus on the recent progress in the light extraction approaches of AlGaN-based UV LEDs, including the highly reflective techniques, and the surface/interface modification for TIR mitigating. Moreover, UV LEDs in the nanoscale, such as nanopillar, nanorod, and nanowire structures, are also discussed.

2 Highly Reflective Techniques for UV Light Emitters

2.1 *Highly Reflective Electrodes*

AlGaN-based UV LEDs usually adopt flip-chip configuration in consideration of the p-GaN light-absorption issue and the thermal management. If a semi- or transparent p-layer and highly reflective structures are introduced on the top side, the upward emission light and the reflected downward light can be then reflected back to the substrate side. In consequence, the escaping probability of photons through the substrate side would be improved.

Inazu et al.[14] presented a 1.55-fold increase in LEE of a sub-300-nm DUV LED using aluminum reflective electrodes deposited to cover both n- and p-type mesh contact electrodes. Meanwhile, the p-GaN layer was partially removed to increase the reflective area. Fayisa et al.[15] fabricated microring array 276-nm LEDs having a p-GaN-removed inner circle of the microrings to reduce the absorption loss in the p-GaN contact layer, together with MgF_2/Al omnidirectional reflectors on the p-GaN etched circle region to redirect the DUV photons impinging on them toward the substrate side. The microring array DUV LED showed remarkably higher light output power (LOP) by 70% than the reference.

To fundamentally avoid the p-GaN absorption problem, Shatalov et al.[17,34] presented a normal incidence optical transmission at 275 nm increasing from 5% in DUV LED with p-GaN contact layer to above 60% in that with transparent p-SPSL. Correspondingly, the absorption coefficient of the p-layer is dramatically reduced to below 1000 cm^{-1}. However, the vertical conductivity of p-SPSL and contact stability then become the crucial issues and need further optimization. Hirayama et al.[16,26,35] demonstrated 140% to 180% improvement in EQE of the 287/279-nm UV LEDs and 60% increase in the electroluminescence (EL) intensity of the 260-nm DUV LED,[36] when using transparent p-AlGaN contact layer and Ni/Al p-type electrode to replace Ni/Au electrode. Yet again, this LED structure without p-GaN contact layer also suffers from increased forward voltage due to higher p-type contact resistance than that in conventional LEDs. Recently, Zheng et al.[37] proposed a multidimensional Mg-doped SL to decrease the hole potential barrier along the c-axis and enhance the vertical hole conductivity, which is ascribed to the stronger p_z hybridization between Mg and N. The grown p-type three-dimensional $\text{Al}_{0.63}\text{Ga}_{0.37}\text{N}/\text{Al}_{0.51}\text{Ga}_{0.49}\text{N}$ SLs have a hole concentration reaching a high value of $3.5 \times 10^{18}\ \text{cm}^{-3}$ and a resistivity as low as $0.7\ \Omega\,\text{cm}$ at room temperature (RT), exhibiting 10 times

Table 1 Current prevailing techniques for UV light extraction.

Group	Year	Structures and techniques	Wavelength (nm)	EQE (%)
RIKEN	2013	Transparent p-AlGaN contact layer and highly reflective p-type electrode[16]	287	5.5 @35 A/cm^2
	2017	Transparent p-AlGaN contact layer, Rh mirror electrode, patterned sapphire substrate, and encapsulation resin[6]	275	20.3 @20 mA
	2018	Highly reflective Ni/Al p-type electrodes[26]	279	9 @20 mA
	2018	HR PhC on p-AlGaN contact layer and reflective Ni/Mg contact layer[27]	283	10 @3 mA
				>8.5 @20 mA
Sensor Electronic Technology, Inc.	2012, 2015	Transparent p-cladding and contact layers, UV reflective ohmic contact, and chip encapsulation[17,28]	278	10.4 @20 mA
National Institute of Information and Communications Technology	2015, 2017	Large-area nanoimprinted AlN nanophotonic light-extraction structure[7,29]	265	4.5 @150 mA
				3.9 @850 mA
UV Craftory Co.	2011	P- and n-mesh contact electrodes covered by aluminum reflective electrodes[14]	288	5.4 @20 mA
	2013	Flip-chip bonding structure with resistant resin encapsulation[30]	280 to 310	10 (max. 14.2)
			260	5
Crystal IS	2013	Die (AlN substrate) thinning and encapsulation[31,32]	271	5.8 @60 mA
			266	5.5 @50 mA
			278	7 @50 mA
Nichia Corp.	2016	With sapphire lens using direct bonding	255	4.56 @100 mA
			280	10.1 @1 A
Pohang University of Science and Technology	2016	Multiple mesa stripes or truncated cone-shaped mesa arrays with inclined sidewalls coated by a MgF_2/Al omnidirectional mirror[20,33]	275	—
			280	—
	2017	5×5 array microring LED with a p-GaN-removed inner circle and inclined sidewalls coated by MgF_2/Al omnidirectional reflectors[15]	276	—
Institute of Semiconductors, Chinese Academy of Sciences	2013	Nano-patterned sapphire substrate[11]	282	3.45 @20 mA

improvement in conductivity compared with that of conventional SLs. Moreover, the resistivity is weakly dependent on temperature. The advances of multidimensional SLs provide a promising solution to reduce the forward voltage of UV LEDs.

Vertical emission can be obtained from the standing wave formed by lateral Bragg resonance in a two-dimensional photonic crystal (PhC) near the quantum-well emission layer.[38] Kashima et al.[27] introduced a highly reflective PhC (HR-PhC) into the surface of the p-AlGaN contact layer to induce the vertical light-propagation. According to their results, the effective reflectance of the HR-PhC p-AlGaN contact layer with the Ni/Mg electrode exceeded 90%. The EQE of

a conventional DUV LED with emission around 283 nm was increased from 4.8% to 10% by using this highly reflective structure.

2.2 *Sidewall Reflection Enhancement Structure*

Highly reflective structure at the slant mesa sidewalls can efficiently deflect the photons guided laterally along the *c*-plane into the vertical direction, which seems a tailored technique for the extraction of TM-polarized light.[39] Lee et al.[20] reported sidewall-emission-enhanced DUV LEDs with active mesa stripes or arrays of truncated cone-shaped active mesas[33] coated with MgF_2/Al reflectors to effectively extract the in-plane TM-polarized emission.

We reported a sidewall reflection enhancement method for AlGaN-based 278-nm LEDs, consisting of mesa microarrays in a hexagonal shape and on-chip highly reflective metal-pads for UV light,[21] as shown in Fig. 1. The total device area was 1 mm^2. Each independent micromesa had a side length of 30 μm and a trapezoidal cross-sectional shape with a slant angle of ∼45 deg after the inductively coupled plasma dry etching. A Ti/Al/Ti/Au metal stack and a Ni/Au metal stack were deposited on the exposed n-AlGaN layer and p-GaN layer to form ohmic contacts, respectively. After the chip passivation with SiO_2, chip-level metal-pads were deposited as anode/cathode electrodes and bond pads as well for the subsequent flip-chip process. Here, we compared the influence of two kinds of metal-pads on the LOP of AlGaN UV LEDs. Cr/Al/Ti/Au system is widely used in the standard 450-nm blue LED fabrication, but Cr metal is not a good UV reflector. In our new method, aluminum-based metal-pads, i.e., Al/Ti/Au, were evaporated, which not only acted as electrodes and bond pads but also covered the trapezoidal mesa sidewall to accommodate the light propagation path. Then, the separated LED chips were flip-chip bonded on silicon submounts with gold bumps for further device testing. It should be noted that the reflectivity of the on-chip metal-pads maintains consistently because of no high-temperature treatment involved.

The average LOP of the encapsulated LEDs with highly reflective metal-pads was increased by 30.1%, compared to that with traditional metal-pads. The improvement is attributed to the less absorption and the more efficient reflection of in-plane guided light arriving at the mesa sidewalls.[39] The LOP can be further increased via reducing the sidewall length of the mesa due to the larger sidewall area for DUV reflection. In addition, there were no significant differences between these two kinds of chips in the electrical properties and the yield, revealing a quite good compatibility of Al/Ti/Au metal-pads in the UV LED fabrication process.

Figure 2 shows the performance of one LED using the sidewall reflection method as a function of the injected CW current. At 100 mA, the LOP reaches 6.8 mW and the forward voltage is about 7 V. When driven to 500 mA, the LED presents a saturation LOP of around 25 mW due to the increased Auger recombination under high current density and heat. The device was stressed at 100 mA CW for >6000 h at RT. The LOP decay shows the L80 (80% of the initial power retention) operation lifetime of ∼5000 h and extrapolated L50 lifetime to >10,000 h.

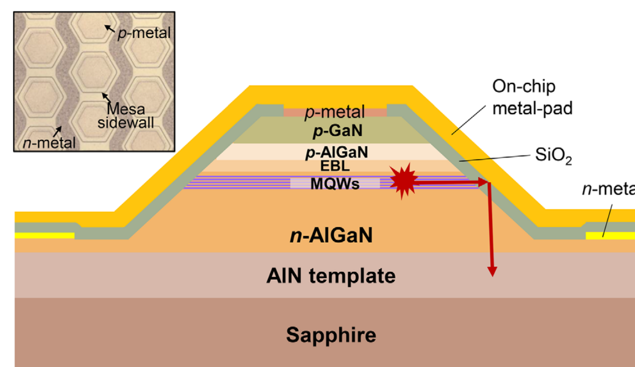

Fig. 1 The schematic structure of AlGaN-based UV LEDs using a sidewall reflection method. Inset: The top-view of the LED chip before the deposition of on-chip metal-pads.

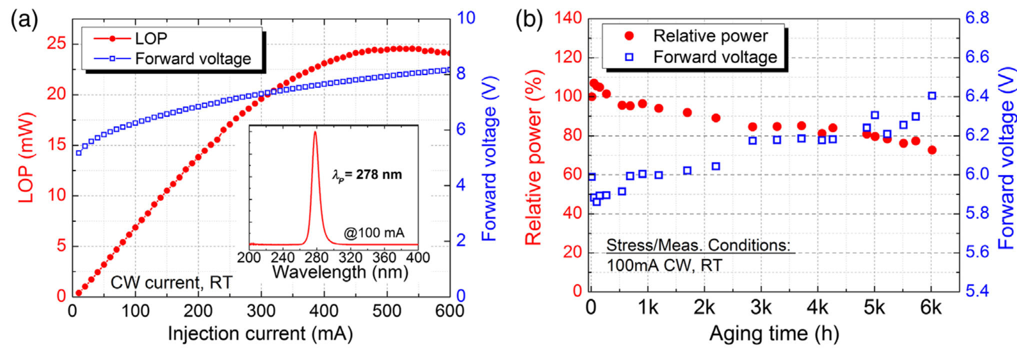

Fig. 2 (a) The typical LOP- and forward voltage-injected CW current characteristics. Inset: the EL spectrum at 100 mA; (b) the reliability test of an encapsulated DUV LED with the sidewall reflection structure at 100-mA CW and RT.

3 Surface/Interface Modification Techniques for UV LEDs

3.1 *Substrate Surface Roughening*

Substrate surface roughening is meant to provide numerous scattering events at the substrate/ambient interfaces for trapped photons to escape from the LED structure. Khizar et al.[40] reported on the fabrication of AlGaN-based 280-nm LEDs with monolithic integrated microlens array on the backside of sapphire substrates and proved a 55% enhancement in LOP at 20 mA compared with the same LED without miroclens. Pernot et al.[41] demonstrated a 50% increase in on-wafer output power of 270-nm LEDs by fabricating a moth-eye structure on the sapphire substrate. Inoue et al.[29] designed hybrid structure nanostructure of PhCs and subwavelength nanostructures on HVPE-AlN substrates. A maximum light extraction enhancement of 196% was obtained in 265-nm LEDs with the hybrid structure in comparison to that of a flat surface device. To enable high-output and high-volume fabrication, they further presented 265-nm DUV LEDs with large-area nanoimprinted AlN nanophotonic structures,[7] which showed wider near-field emitting areas, stronger far-field extracted light intensities, and an approximately 20-fold increase in LOP compared with a conventional flat-surface LED.

3.2 *Substrate Sidewall Roughening*

As mentioned above, the TM-polarized light propagates mainly in the lateral direction and is extracted from the device sidewalls. Hence, it is also important to pay attention to the sidewall TIR mitigation such as roughening the device sidewalls, especially the substrate sidewalls that have lager area than the epitaxial layer sidewalls.

Substrate sidewall roughening can be realized by ultrashort pulse laser stealth dicing during the chip-separation process and has been proven to be helpful to enhance the LEE in visible and UV LEDs.[42–45] Lee at al.[45] demonstrated that thick sapphire substrates with roughened sidewalls are critical for TM-polarized photons from the AlGaN quantum wells to escape in lateral direction before they are absorbed by p-GaN and metal electrodes. We investigated the effect of sapphire substrate's sidewall roughening on the light extraction behavior of AlGaN-based 275-nm UV LEDs by finite-difference time-domain (FDTD) simulation and experimental output power measurement.[46]

Figure 3(a) shows the FDTD computational domain of the UV LED with a roughened sapphire substrate reference sidewall. For a given TE- or TM-mode dipole with a distance d from the reference sidewall, its light extraction is enhanced only when the roughening position z is within a specific region (not shown here), which is defined as the effective roughening region. As shown in Fig. 3(b), the effective roughening region is between the substrate's backside and the lower boundary $\sim d \times \tan(\theta c)$, where θc is the TIR critical angle. Roughening outside the effective roughening region will reduce the sidewall LEE due to the undesirable inward photon scattering at the substrate sidewall. The extracted light power of various dipoles with different positions was simulated individually and then combined to obtain the overall light extraction enhancement

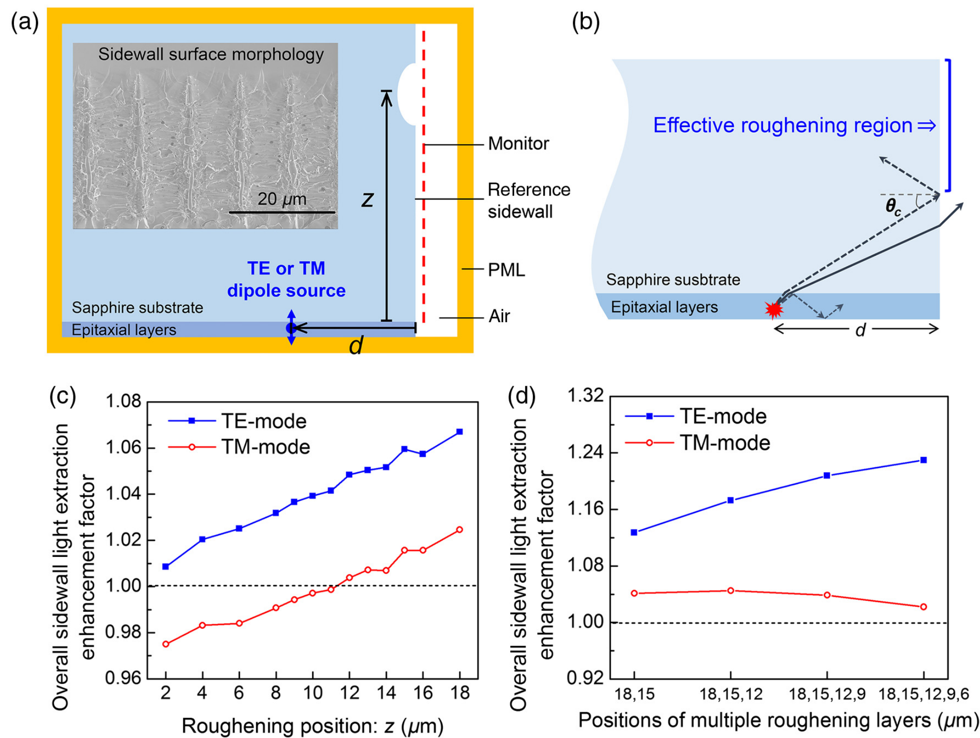

Fig. 3 (a) Schematic diagram of the FDTD computational domain of the UV LED structure with the roughened sapphire sidewall. Inset: Scanning electron microscopy (SEM) image of sidewall morphology of one roughening layer.[46] (b) Schematic diagram of the effective roughening region for one dipole on the reference sidewall. The dependence of overall sidewall light extraction enhancement factor on the position of (c) a single roughening layer and (d) multiple roughening layers.

factor with respect to the roughening position. As shown in Fig. 3(c), the overall extraction efficiency of TE-mode light keeps improved regardless of the roughening position z on the substrate sidewall. In contrast, the overall extraction of TM-mode light encounters a decrease when the roughening position z is lower than a certain value, revealing that a roughening region for effective light extraction enhancement exists on the substrate's sidewall. Moreover, the boundary of the overall effective roughening region of TM mode is found equal to that of the TM-polarized dipole in the center of the active region.[46] A simulation with multiple roughening layers in Fig. 3(d) further verified the effective roughening region assumption. Therefore, the effective roughening region of TM polarization in one LED with a side length of L is deduced to from the sapphire substrate's backside to the position $\sim L/2 \times \tan(\theta c)$.

We designed four sidewall roughening schemes for TM-mode-dominant UV LEDs. As shown in Fig. 4, the LEDs with three roughening layers have 13.2% higher LOP at 20 mA than those with two roughening layers, due to the larger roughening area in the effective roughening region. However, when further applying additional roughening layers beyond the effective roughening region, the LOP decreases, which is in consistent with the simulation result. The current–voltage characteristics of these LEDs were similar, indicating that the LOP variation mainly comes from different roughening schemes. Therefore, depth-controlled substrate's sidewall roughening is beneficial to maximize the LOP of AlGaN-based UV LEDs.

3.3 *Substrate Shaping*

Modifying the geometry of the LED chip can also help outcouple the light trapping in the structure. It could be regarded as the upscaling of the surface texturing.[47] Krames et al.[48] fabricated truncated-inverted-pyramid AlGaInP-based LEDs sawn by a beveled dicing blade, exhibiting 40% improvement in EQE compared to the conventional devices. Lee et al.[49] reported 55% light output enhancement in flip-chip GaN-based LEDs with oblique sapphire sidewalls on the bottom of the substrate using a wet etching technique.

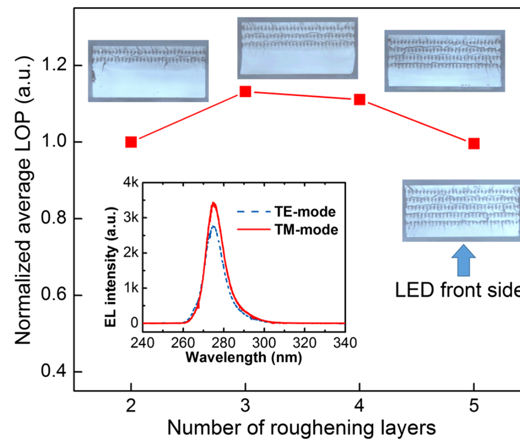

Fig. 4 The normalized average LOP of LEDs at 20 mA. Inset: The EL spectra of the LED wafer for TE- and TM-modes at 20 mA.

Laser micromachining has been introduced to shape the sapphire substrate, such as nanosecond laser dicing either with a laser-beam turning mirror[50] or with an oblique sample stage[51] to bevel the substrate sidewalls and shifted picosecond (ps) laser stealth dicing to form wavy substrate sidewalls.[52] We proposed a convenient ps laser multiple scribing method to shape the sapphire substrates into an oblique sidewall geometry for enhanced LEE.[53] In general, the scribing lines beneath the same street are distributed in the same vertical plane inside the substrate; thus, the LEDs have vertical sidewalls after splitting. In our study, the applied multiple scribing lines beneath the same street are intentionally aligned along an oblique plane with designed angles to guide the chip splitting direction. The LED chips are thereby shaped into an oblique sidewall geometry. Compared with the convention chip with vertical sidewalls, the 276-nm LED with two opposite sidewalls partially shaped with 60 deg inclination shows 13.8% higher LOP at 50 mA. The FDTD simulation reveals that this oblique substrate sidewall geometry is effective for TM-polarized light extraction.

3.4 *Interface Modification*

According to the simulations[12,21,54] and experimental results, a large amount of TE- and TM-polarized light encounter TIR at the interfaces among the substrate, AlN layer, n-AlGaN layer, multiple-quantum-well region, electron blocking layer, and p-AlGaN cladding layer, resulting in light confinement and absorption. A careful consideration should be given to the interface modification, or in other words, effective refraction index adjustment around the interfaces.

The AlN epitaxial lateral overgrowth on pattered substrates or templates can not only improve the crystal quality of the overgrown epitaxial layers but also form embedded air voids in the AlN layer (as shown in Fig. 5).[11,35,55–57] The effective refraction index around the interface is thereby between the AlN layer and the substrates (or the templates). The light scattering at the interface reduces the TIR and increases the photons' escape opportunity. We reported AlGaN-based 282-nm LEDs grown on nanopatterned sapphire substrates (NPSS), exhibiting 98% better performance relative to those grown flat sapphire substrate.[11] The internal quantum efficiency (IQE) enhancement is estimated to be 60% enhancement, so the LEE enhancement would be more than 20%. Lee et al.[56] fabricated DUV LEDs on NP-AlN/sapphire templates, with air surrounding the AlN nanorods. Light emitted from the multiple quantum wells can propagate vertically by passing through the embedded nanostructures and thus the TIR is avoided.

4 Nanostructure UV LEDs

The nanostructures, including nanorods, nanopillars, nanowires, or other structures in the nanoscale, have been found to be quite effective in improving the LEE of AlGaN-based UV LEDs.

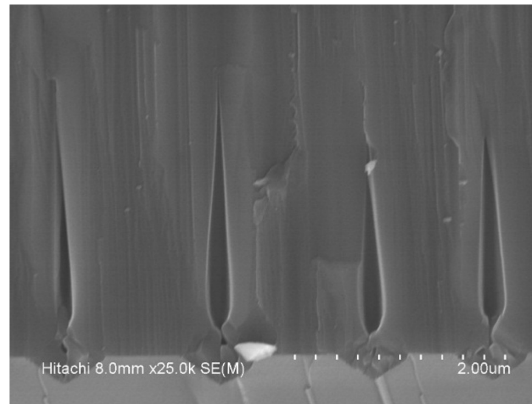

Fig. 5 A cross-sectional SEM image of overgrown AlN on NPSS.

Ryu's study showed that the LEE from the top surface can be higher than 50% and 60% for TE- and TM-polarized lights, respectively, when the structural parameters of the nanorod LED are optimized for the formation of resonant modes inside the nanorod structure.[58] Zhao et al.[19] reported an efficient surface-emitting near-vacuum UV nanowire LED through direct electrical injection. By optimizing the nanowire diameter and spacing, the dominated light emission can be from the nanowire top surface due to the multiple light coupling and scattering process, albeit the light is TM polarized. Djavid et al.'s simulation showed that the emission of the guided modes in DUV LEDs can be inhibited and redirected into radiated modes utilizing nanowire structure.[59,60] Alias et al.[61] demonstrated an AlGaN nanowire LED integrated with nitride/air distributed Bragg reflector nanogratings to enhance the LEE. Compared to the control AlGaN NW-LED, the LED with the nanogratings exhibited higher LOP by a factor of ∼1.67 at 50 mA injected current, which is attributed to the coupling of the in-plane backreflected light from the nanogratings and the out-of-plane emission. In addition, the nonvertical sidewalls of the nanogratings also facilitate the in-plane light to scatter to the out-of-plane emission.

Nanostructured AlGaN-based UV LEDs can be obtained either by the bottom-up growth or top-down etching method. Using the former bottom-up method mainly by molecular beam epitaxy, nearly defect-free Al(Ga)N nanowires/nanorods can be grown on foreign substrates with high internal quantum efficiency (IQE).[62–64] Moreover, the enhanced Mg-dopant incorporation and the reduced activation energy of Mg dopant in nanostructures lead to significantly improved p-type doping efficiency and more efficient current injection. But it should be mentioned that the inhomogeneity of the nanostructures can cause unexpected light confinement and material light-absorption loss.

In contrast, ordered nanostructures can be achieved via the latter etching method.[18,65] We fabricated nanopillar AlGaN/GaN multiple quantum wells UV LEDs by nanosphere lithography and dry-etching.[18] The simulated LEE from the top surface, bottom surface, and the sidewalls in the nanopillar LED is 2.2, 1.8, and 0.73 times of those in the planar LED, respectively. Although the LEE from the sidewalls is decreased, the total LEE is still increased from 22.5% to 33.7% due to the greatly enhanced LEE in the vertical direction. In addition, the strain is partially released in the epitaxial layers of the nanopillar LED, resulting in suppressed quantum confined stark effect and a 42% enhanced IQE at RT.

5 Conclusions

This study reviewed the recent progress in the light extraction approaches of AlGaN-based UV LEDs, including the highly reflective techniques and the surface/interface modification for TIR mitigating. Moreover, AlGaN-based UV LEDs in the nanoscale structures, such as nanopillar, nanorod, and nanowire structures, are also discussed. Nanostructured UV LEDs have been found to be quite effective in improving the LEE especially the LEE of TM-polarized light.

Disclosures

The authors declare no competing financial interests.

Acknowledgments

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Yanan Guo is an assistant professor at the Institute of Semiconductors, Chinese Academy of Sciences. She received her BS degree in physics from Xiamen University in 2012, and her PhD in materials physics and chemistry from the University of Chinese Academy of Sciences in 2017. Since then, she joined the Semiconductor Lighting R&D Center of CAS to continue the research.

Her current research interests are mainly focused on the performance enhancement of AlGaN-based ultraviolet emitters.

Jianchang Yan, PhD, is a professor at the Institute of Semiconductors, Chinese Academy of Sciences. He received his bachelor's degree from Tsinghua University, and his PhD in microelectronics and solid-state electronics from the Graduate University of Chinese Academy of Sciences. In 2009, he joined the Semiconductor Lighting R&D Center of CAS to continue the research work on III-nitride material and devices. He was visiting scholar of Paris Sud University in 2015 to 2016. He is the leader of the III-nitride ultraviolet light-emitting device group, focusing on the research of Al(Ga)N-based UV LEDs and UV LDs.

Biographies for the other authors are not available.