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Deep Ultraviolet AlGaN-Based Light-Emitting Diodes with p-AlGaN/AlGaN Superlattice Hole Injection Structures

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Abstract: The p-AlGaN/AlGaN superlattice (SL) hole injection structure was introduced into deep ultraviolet (DUV) light-emitting diodes (LEDs) to enhance their performances. The period thicknesses of the p-$Al_{0.8}Ga_{0.2}N/Al_{0.48}Ga_{0.52}N$ SLs affected the performances of the DUV LEDs. The appropriate period thickness of the p-$Al_{0.8}Ga_{0.2}N/Al_{0.48}Ga_{0.52}N$ SL may enhance the hole injection of DUV LEDs. Therefore, compared with the reference LEDs, the DUV LEDs with the 10-pair $Al_{0.8}Ga_{0.2}N$ (1 nm)/$Al_{0.48}Ga_{0.52}N$ (1 nm) SL presented forward voltage reduction of 0.23 V and light output power improvement of 15% at a current of 350 mA. Furthermore, the 10-pair $Al_{0.8}Ga_{0.2}N$ (1 nm)/$Al_{0.48}Ga_{0.52}N$ (1 nm) SL could slightly suppress the Auger recombination and current overflow of the DUV LEDs in a high-current operation region. In addition to improved carrier injection, the DUV LEDs with the p-$Al_{0.8}Ga_{0.2}N/Al_{0.48}Ga_{0.52}N$ SL hole injection structure showed reduced light absorption at their emission wavelength compared with the reference LEDs. Therefore, the DUV LEDs with p-$Al_{0.8}Ga_{0.2}N/Al_{0.48}Ga_{0.52}N$ SL may exhibit better light extraction efficiency than the reference LEDs. The enhancement of p-$Al_{0.8}Ga_{0.2}N$ (1 nm)/$Al_{0.48}Ga_{0.52}N$ (1 nm) SL may contribute to improvements in light extraction and hole injection.

Keywords: AlGaN superlattice; hole injection; light-emitting diode

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1. Introduction

AlGaN-based deep ultraviolet (DUV) light-emitting diodes (LEDs) have attracted attention in many fields, such as ultraviolet photolithography, high-density optical data storage, water purification, and portable chemical/biological agent detection/analysis systems [1–5]. The quality of AlGaN material has been greatly improved because of the optimization of epitaxy techniques; this improvement has also greatly enhanced the light-emission efficiency of DUV LEDs [6–11]. Despite the dramatic improvements in DUV LED performance, AlGaN-based DUV LEDs continue to face the problems of high-defect density and low-hole concentrations of high Al-content AlGaN material. Since the initial study on GaN-based LEDs, the low-hole concentrations of p-type GaN-based material has been a major issue that limits the efficiency of GaN-based LEDs because it causes poor hole injection [12–17]. Moreover, the problem of low-hole concentration for p-type $Al_xGa_{1-x}N$ with $x > 0.5$ is worsening [10–13]. The doping efficiency for AlGaN with high Al content is still far from satisfactory due to a combination of factors involving limited solubility, high activation energy, increased donor compensations, and increased hole scatterings [14,15]. The p-type AlGaN/GaN heterojunction [18–20] and the AlGaN/GaN superlattice (SL) [21–28] have been reported to increase the hole concentrations of p-type

GaN-based materials. Since then, similar concepts have been applied in many studies on GaN-based LEDs; such concepts include AlGaN/GaN/AlGaN quantum wells [29,30], AlGaN/GaN SLs [31], and graded AlGaN/GaN SLs [32,33]. Considering that the p-type AlGaN/GaN SL structure has presented promising results in GaN-based LEDs, a similar idea has been adopted to improve the hole concentration of high-Al content AlGaN in DUV LEDs [34,35]. Besides, p-AlGaN/AlGaN SL could also improve light extraction efficiency (LEE) of DUV LEDs [36]. Although the p-AlGaN/AlGaN SL structure has been proposed in many studies on DUV LEDs, revealing its other effects on DUV LEDs remains worthy. In this work, we replaced the hole injection layer of the 20 nm thick Mg-doped $Al_{0.48}Ga_{0.52}N$ layer in the structure of the DUV LEDs with Mg-doped $Al_{0.8}Ga_{0.2}N/Al_{0.48}Ga_{0.52}N$ SLs. The total thickness of the Mg-doped $Al_{0.8}Ga_{0.2}N/Al_{0.48}Ga_{0.52}N$ SLs was kept at 20 nm. We prepared Mg-doped $Al_{0.8}Ga_{0.2}N/Al_{0.48}Ga_{0.52}N$ SLs with different period thicknesses to understand how period thickness affected the optoelectrical characteristic of DUV LEDs. The theoretical (simulation) and experimental results for the DUV LEDs with the Mg-doped $Al_{0.8}Ga_{0.2}N/Al_{0.48}Ga_{0.52}N$ SL hole injection layer, the electrical and optical properties of AlGaN-based DUV LEDs, and the fabrication process, were discussed in this study.

2. Materials and Methods

AlGaN-based DUV LEDs were epitaxially grown on a 2-inch (0001) sapphire substrate by using a Thomas Swan close-coupled showerhead 31 × 2-inch metalorganic chemical vapor deposition (MOCVD) system. In MOCVD growth, trimethylgallium, trimethylaluminum, and ammonia were used as the source materials of Ga, Al, and N, respectively. Biscyclopentadienyl magnesium and silane were used as p-type and n-type doping sources, respectively. A 20 nm thick AlN nucleation layer was grown on the sapphire substrate at the reactor temperature of 500 °C. The growth temperature was raised to 1250 °C for the growth of the 3 μm thick undoped AlN epitaxial layer. The screw and edge dislocation density of our AlN samples were 1.03×10^8 cm^{-2} and 1.64×10^9 cm^{-2}, respectively. The AlN epitaxy layer was followed by the epitaxy of a 1.5 μm thick Si-doped $Al_{0.6}Ga_{0.4}N$ layer. The DUV light-emitting MQW structure with 5-pair $Al_{0.6}Ga_{0.4}N$:Si (12 nm)/$Al_{0.4}Ga_{0.6}N$ (2 nm) was grown at the reactor temperature of 1050 °C. A 2 nm thick undoped $Al_{0.65}Ga_{0.35}N$ last thin barrier was then grown on the 5-pair $Al_{0.6}Ga_{0.4}N$ (12 nm)/$Al_{0.4}Ga_{0.6}N$ (2 nm) DUV MQW. An electron blocking layer (EBL) with a 7 nm-thick undoped $Al_{0.7}Ga_{0.3}N$ layer and Mg-doped 3-pair AlGaN (7.5 nm)/AlGaN (3.5 nm) was grown on the $Al_{0.65}Ga_{0.35}N$ last thin barrier. A 20 nm thick Mg-doped $Al_{0.48}Ga_{0.52}N$ hole injection layer was grown on the EBL for the standard DUV LEDs as a reference. The SL structures of 5-pair $Al_{0.8}Ga_{0.2}N$ (2 nm)/$Al_{0.48}Ga_{0.52}N$ (2 nm), 10-pair $Al_{0.8}Ga_{0.2}N$ (1 nm)/$Al_{0.48}Ga_{0.52}N$ (1 nm), and 15-pair $Al_{0.8}Ga_{0.2}N$ (0.66 nm)/$Al_{0.48}Ga_{0.52}N$ (0.66 nm) were separately grown on EBL instead of the Mg-doped $Al_{0.48}Ga_{0.52}N$ hole injection layer for the studied DUV LEDs. Then, the full structure of DUV LEDs was ended with a 20 nm thick Mg-doped graded Al composition AlGaN layer and a 10 nm thick Mg-doped GaN layer. The Al composition in the 20 nm thick Mg-doped graded Al composition AlGaN layer was linearly decreased from 47% to 25%.

Subsequently, standard processing steps were performed to fabricate 1000 μm × 1000 μm flip-chip DUV LEDs. The details of the flip-chip DUV LEDs and mounting processes were reported in our previous study [37]. The scheme of the DUV LED structures, the schematic and image of the flip-chip DUV LEDs, and the transmission electron microscopy (TEM) images of standard DUV LEDs and DUV LEDs with 10-pair $Al_{0.8}Ga_{0.2}N$ (1 nm)/$Al_{0.48}Ga_{0.52}N$ (1 nm) are shown in Figure 1. The standard DUV LEDs are denoted as the reference LEDs. The DUV LEDs with the 5-pair $Al_{0.8}Ga_{0.2}N$ (2 nm)/$Al_{0.48}Ga_{0.52}N$ (2 nm), 10-pair $Al_{0.8}Ga_{0.2}N$ (1 nm)/$Al_{0.48}Ga_{0.52}N$ (1 nm), and 15-pair $Al_{0.8}Ga_{0.2}N$ (0.66 nm)/$Al_{0.48}Ga_{0.52}N$ (0.66 nm) SL hole injection layers are denoted as LED 2/2, LED 1/1, and LED 0.66/0.66, respectively. The current–voltage (I–V) characteristics of the fabricated flip-chip DUV LEDs were measured by using a Keysight B1500 and HP-4156B semiconductor parameter analyzer for high-current and low-current measurements, respectively. The output power and emission spectra of the LEDs were acquired at room temperature by using a calibrated integrating sphere and a spectrometer (Ocean Optics USB2000).

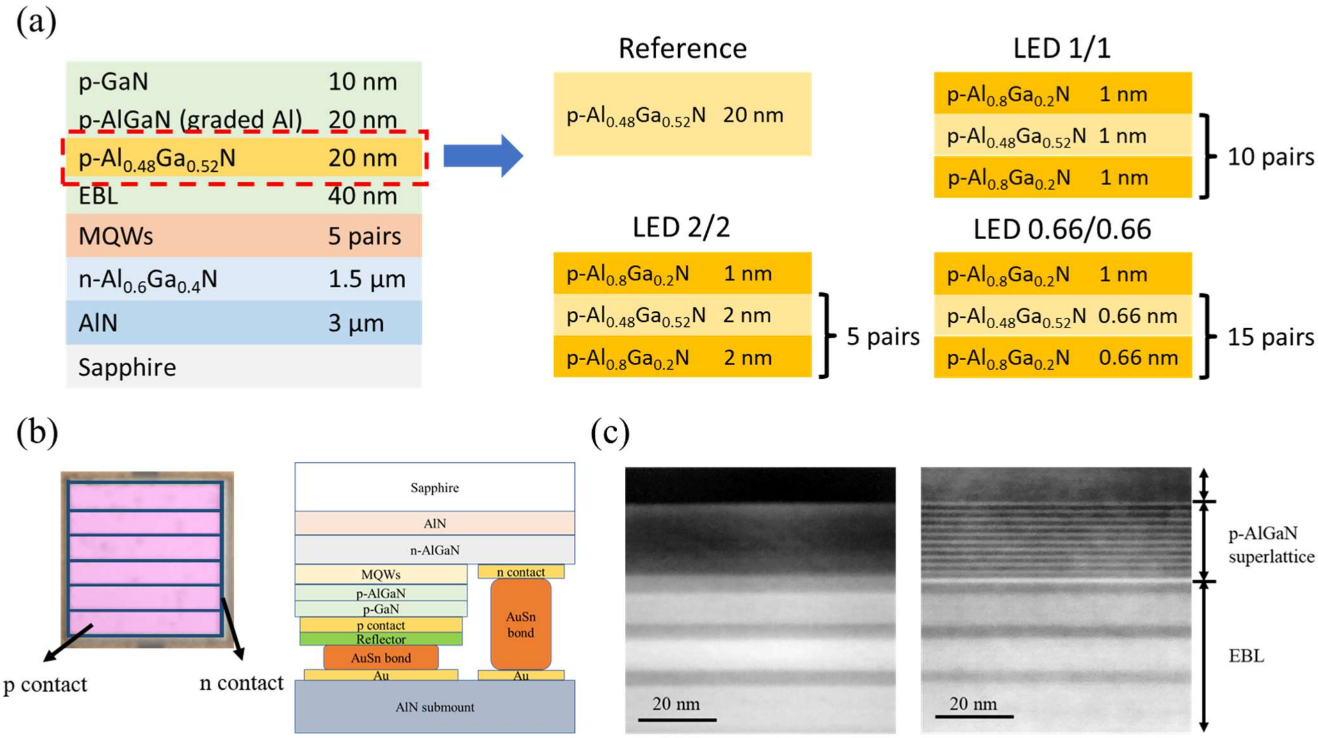

Figure 1. (**a**) Schematic of DUV LEDs with different p-AlGaN/AlGaN SLs; (**b**) schematic and image of the flip-chip DUV LEDs; (**c**) TEM images of standard DUV LEDs and DUV LEDs with 10-pair $Al_{0.8}Ga_{0.2}N$ (1 nm)/$Al_{0.48}Ga_{0.52}N$ (1 nm).

3. Results and Discussion

The I–V characteristics and dynamic resistance of all flip-chip DUV LEDs were investigated, as presented in Figure 2. The 350 mA forward voltages (V_f) of the reference LED, LED 2/2, LED 1/1, and LED 0.66/0.66 were 6.69, 6.73, 6.46, and 6.38 V, respectively. The average Al composition of p-$Al_{0.8}Ga_{0.2}N$/$Al_{0.48}Ga_{0.52}N$ SLs was 0.64, and it was higher than that of p-$Al_{0.48}Ga_{0.52}N$ bulk. The LEDs with p-$Al_{0.8}Ga_{0.2}N$/$Al_{0.48}Ga_{0.52}N$ SLs were expected to possess higher V_f due to higher series resistance. However, the reference LED and LED 2/2 exhibited close V_f. Moreover, the V_f of the DUV LEDs continuously decreased as the period thickness of the p-$Al_{0.8}Ga_{0.2}N$/$Al_{0.48}Ga_{0.52}N$ SL was decreased. Contrary to bulk, SLs possessed poor vertical conductivity and better lateral conductivity [25–28]. The V_f reduction of LEDs with p-$Al_{0.8}Ga_{0.2}N$/$Al_{0.48}Ga_{0.52}N$ SL could mainly contribute to improved current spreading. Regarding the period thickness of SL, the vertical conductivity of SL with short period thickness was higher than that of SL with long period thickness, but the lateral conductivity of SL with short period thickness was lower than that of SL with long period thickness [25–28]. In our results, the V_f of the DUV LEDs decreased as the period thickness of SL was decreased, and it indicated that the extent of vertical conductivity change could be more than that of lateral conductivity change as the period thickness of SL was decreased. Figure 2a shows the forward voltage dependent dynamic resistances of all DUV LEDs. The dynamic resistances of all DUV LEDs individually converged to a value when the forward voltage was larger than 6.5 V. The dynamic resistance near the V_f of the reference LEDs, LED 2/2, LED 1/1, and LED 0.66/0.66 were 19.1, 19.2, 18.4, and 18.2 Ω, respectively. The reference LED and LED 2/2 had almost the same dynamic resistance. Thus, the reference LED and LED 2/2 had close V_f. In addition, the dynamic resistance of the DUV LEDs decreased as the period thickness of the p-$Al_{0.8}Ga_{0.2}N$/$Al_{0.48}Ga_{0.52}N$ SLs was decreased. The hole energy state in the well of the $Al_{0.8}Ga_{0.2}N$/$Al_{0.48}Ga_{0.52}N$ SLs would be increased by reduction of the thickness of well. Besides, reduction of the barrier thickness may increase the tunneling probability of the hole carrier. This phenomenon effectively reduced the potential barrier on the hole carrier at interface of the EBL and $Al_{0.8}Ga_{0.2}N/Al_{0.48}Ga_{0.52}N$ SLs. Therefore, LED 1/1 and 0.66/0.66 exhibited lower dynamic resistance than the reference LEDs and LED 2/2.

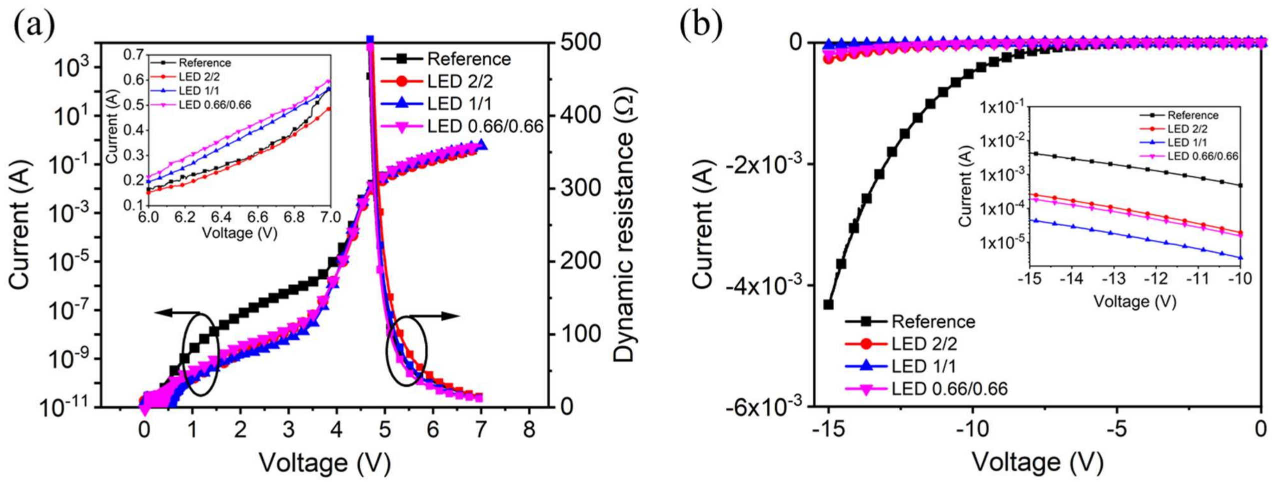

Figure 2. (**a**) Semi-log forward I–V of DUV LEDs with different p-AlGaN/AlGaN SLs. The inset of Figure 2a presents linear forward I–V curves of DUV LED samples at voltage range of 6–7 V. (**b**) Linear reverse I–V of DUV LEDs with different p-AlGaN/AlGaN SLs. The inset of Figure 2b presents semi-log reverse I–V curves of DUV LED samples at voltage range of −10–15 V.

In addition to their reduced V_f and dynamic resistance, the DUV LEDs with the proposed p-$Al_{0.8}Ga_{0.2}N/Al_{0.48}Ga_{0.52}N$ SL hole injection layer exhibited reduced current at applied voltages less than 3 V compared with the reference LEDs. The reduction in current at the applied voltage of 3 V implied that the DUV LEDs with the p-$Al_{0.8}Ga_{0.2}N/Al_{0.48}Ga_{0.52}N$ SL hole injection layer had a lower defect-assisted recombination current than the reference LED. Besides, since the average Al composition of SLs (x = 0.64) was higher than the Al composition of bulk (x = 0.48), SLs would possess larger potential barrier than bulk. Additionally, the potential barrier could be enhanced by the piezoelectric field of SLs. As a result, the reduction in current at applied voltages less than 3V could contribute to large potential of SLs. Moreover, the proposed p-$Al_{0.8}Ga_{0.2}N/Al_{0.48}Ga_{0.52}N$ SL hole injection layer improved the reverse I–V characteristics of the DUV LEDs. In Figure 2b, the reverse current at −15 V of the reference LEDs could be significantly reduced from -4.95×10^{-3} A to -4.57×10^{-5} A by replacing the p-AlGaN hole injection layer with the p-$Al_{0.8}Ga_{0.2}N/Al_{0.48}Ga_{0.52}N$ SLs. The p-$Al_{0.8}Ga_{0.2}N/Al_{0.48}Ga_{0.52}N$ SLs exhibited clear and sharp high-quality $Al_{0.8}Ga_{0.2}N/Al_{0.48}Ga_{0.52}N$ interfaces in the TEM image provided in Figure 1c. The multiple high-quality $Al_{0.8}Ga_{0.2}N/Al_{0.48}Ga_{0.52}N$ interfaces might have covered the pits and defects at the bottom of the structure well. Sun et al. [38] reported that threading dislocations (TDs) of AlGaN could be improved by inserting AlN/AlGaN superlattice. The AlN/AlGaN superlattice could function as dislocation filter, and it could benefit from the AlN/AlGaN SL coherent growth. Therefore, this phenomenon could explain the I–V characteristics at low forward voltage and the improvement in the reverse I–V characteristics of the DUV LEDs.

The hole injection of the DUV LEDs may be improved by replacing the p-AlGaN hole injection layer with the p-$Al_{0.8}Ga_{0.2}N/Al_{0.48}Ga_{0.52}N$ SLs. This effect could result in the enhancement of the light output power of the DUV LEDs. Mondal et al. [11] and Yang et al. [12] have reported simulation results for similar DUV LED structures. They concluded that after the EBL of DUV LEDs, SLs or multilayer p-AlGaN/AlGaN structures effectively increased hole injection in the MQW region to enhance the light output power of the DUV LEDs. Figure 3 shows the measured output powers and external quantum efficiencies (EQEs) of all DUV LEDs as a function of the injection current density. The light output powers of the DUV LEDs driven at a current density of 350 A/cm^2 were 42.74, 40.81, 49.24, and 44.57 mW, which corresponded to EQEs of 2.68%, 2.58%, 3.15%, and 2.83% for the reference LEDs, LED 2/2, LED 1/1, and LED 0.66/0.66, respectively. The light output power of the DUV LEDs with 5-pair $Al_{0.8}Ga_{0.2}N$ (2 nm)/$Al_{0.48}Ga_{0.52}N$ (2 nm) was approximately 5% less than that of reference LEDs. Comparison with the reference LED revealed that the DUV LEDs with 10-pair $Al_{0.8}Ga_{0.2}N$ (1 nm)/$Al_{0.48}Ga_{0.52}N$ (1 nm) presented the light output power enhancement of 15%, which was the largest improvement observed in this study. However, the enhancement in light output power decreased to 4.3% when the pair thickness of the p-$Al_{0.8}Ga_{0.2}N/Al_{0.48}Ga_{0.52}N$ SLs was reduced to 1.32 nm. Relative to that of the reference LEDs, the light output power enhancement of the DUV LEDs with the p-$Al_{0.8}Ga_{0.2}N/Al_{0.48}Ga_{0.52}N$ SLs was strongly affected by the pair thickness of the hole injection layer. Furthermore, the proposed p-$Al_{0.8}Ga_{0.2}N/Al_{0.48}Ga_{0.52}N$ SL hole injection layer could slightly change the behavior of the efficiency droops of the DUV LEDs. The efficiency droops of the reference LED, LED 2/2, LED 1/1, and LED 0.66/0.66 were 36%, 37%, 31%, 34%, respectively. (The efficiency droop was defined as the EQE degradation from the peak of EQE to the EQE at current of 800 mA, efficiency droop = $1 - \frac{EQE_{peak}}{EQE_{800mA}}$.)

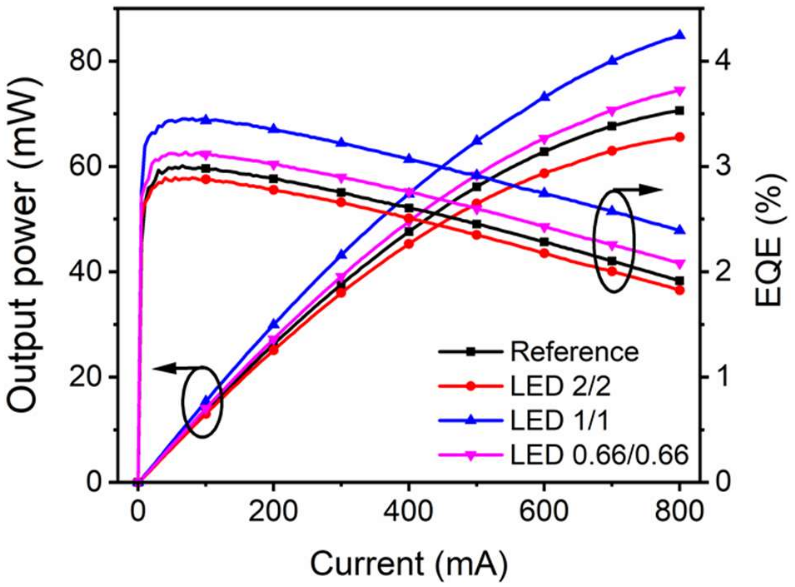

Figure 3. Current-dependent output power and EQE of DUV LEDs with different p-AlGaN/AlGaN SLs.

The light output power of LED 2/2 was reduced compared with that of the reference LEDs. Given that LED 2/2 had a slightly higher V_f and dynamic resistance than the reference LEDs, these results implied that the 5-pair $Al_{0.8}Ga_{0.2}N$ (2 nm)/$Al_{0.48}Ga_{0.52}N$ (2 nm) SL did not improve hole injection. Although the lateral conductivity of SL could be improved, the poor vertical conductivity of SL could weaken the hole injection. The long period thickness of 5-pair $Al_{0.8}Ga_{0.2}N$ (2 nm)/$Al_{0.48}Ga_{0.52}N$ (2 nm) SL may reduce hole transport despite the improved lateral conductivity. As the period thickness of SL was reduced, the lateral conductivity of SL decreased, and the vertical conductivity of SL increased. The 10-pair $Al_{0.8}Ga_{0.2}N$ (1 nm)/$Al_{0.48}Ga_{0.52}N$ (1 nm) SL might suffer decreased lateral conductivity, but it benefited from better vertical conductivity. Therefore, the enhanced output power of DUV LED with 10-pair $Al_{0.8}Ga_{0.2}N$ (1 nm)/$Al_{0.48}Ga_{0.52}N$ (1 nm) SL could have contributed to better hole injection. When the period thickness was further reduced, the 15-pair $Al_{0.8}Ga_{0.2}N$ (0.66 nm)/$Al_{0.48}Ga_{0.52}N$ (0.66 nm) SL might have suffered more decreased lateral conductivity despite improved vertical conductivity. In this case, the current spreading of 15-pair SL declined, and the enhancement of output power of

DUV LED with 15-pair SL was lowered. In the perspective of the efficiency droops of our DUV LEDs, the reference LED and LED 2/2 possessed similar efficiency droop, and it indicated that the hole injection of reference LED was similar to that of LED 2/2. However, the LED 1/1 possessed slightly improved efficiency droop, and it also implied that the 10-pair SL could also improve current spreading. In the high-current injection region, the effects of Auger recombination and current overflow of LEDs could be dominant. The improved current spreading could suppress the effects of Auger recombination and current overflow. The LED 0.66/0.66 had larger efficiency droop than that of LED 1/1. It may be caused by reduced current spreading due to decreased lateral conductivity. The weakened current spreading could augment the effects of Auger recombination and current overflow. Hence, the efficiency droop of LED 0.66/0.66 worsened. The 10-pair $Al_{0.8}Ga_{0.2}N$ (1 nm)/$Al_{0.48}Ga_{0.52}N$ (1 nm) SL may be the optimal SL structure in this study because the DUV LEDs with this SL structure had the best electrical properties and the highest light output power. The appropriate period thickness of $Al_{0.8}Ga_{0.2}N$/$Al_{0.48}Ga_{0.52}N$ SL may enhance hole injection efficiency to improve light output power and suppress the effects of Auger recombination and current overflow under high-current operation.

In addition to enhancing hole injection, the p-$Al_{0.8}Ga_{0.2}N$/$Al_{0.48}Ga_{0.52}N$ SLs would modify the transmittance spectra of the DUV LEDs. Figure 4 shows the transmittance spectra of the reference LED, LED 2/2, LED 1/1, and LED 0.66/0.66. All DUV LED samples presented high transmittance in the visible-light wavelength region. However, the values varied among the samples. All DUV LED samples showed stepwise decrements in transmittance. The initial reduction in the transmittance of all DUV LEDs occurred at a wavelength near 365 nm, which corresponded to the absorption of the p-GaN contact layer. The second decrement in the transmittance of all DUV LEDs occurred at a wavelength near 275 nm and should originate from the absorption of AlGaN/AlGaN MQWs and other AlGaN layers with band gaps near 4.52 eV. However, the reference LEDs showed the lowest transmittance values within the wavelength range of 250–280 nm. The strong absorption of the reference LEDs within the wavelength range of 250–280 nm should be attributed to the absorption of the $Al_{0.6}Ga_{0.4}N$ (12 nm)/$Al_{0.4}Ga_{0.6}N$ (2 nm) DUV MQW and p-$Al_{0.48}Ga_{0.52}N$ hole injection layer. The p-$Al_{0.8}Ga_{0.2}N$/$Al_{0.48}Ga_{0.52}N$ SL hole injection layer possessed a larger effective band gap than the p-$Al_{0.48}Ga_{0.52}N$ hole injection layer. The effective band gap would be enlarged by reducing the pair thickness of the p-$Al_{0.8}Ga_{0.2}N$/$Al_{0.48}Ga_{0.52}N$ SLs. Therefore, LED 1/1 and LED 0.66/0.66 presented the highest transmittance within the wavelength range of 250–280 nm. The transmittance of DUV LEDs could be qualitatively related to light extraction efficiency (LEE) of DUV LEDs [36]. Comparing the output power results in Figure 3 with the transmittance results in Figure 4, the transmittance of LED 2/2 was higher that of reference LED within the wavelength range of 250–280 nm, but the output power of LED 2/2 was lower than that of reference. It implied that internal quantum efficiency (IQE) of LED 2/2 was lower than that of reference. This result also indicated that the hole injection of 5-pair SL was not improved. Both LED 1/1 and LED 0.66/0.66 possessed the highest transmittance within the wavelength range of 250–280 nm, but the output power of LED 0.66/0.66 was lower than that of LED 1/1. It also implied that the IQE of LED 0.66/0.66 was worse than that of LED 1/1. This can contribute to weakened current spreading due to decreased lateral conductivity.

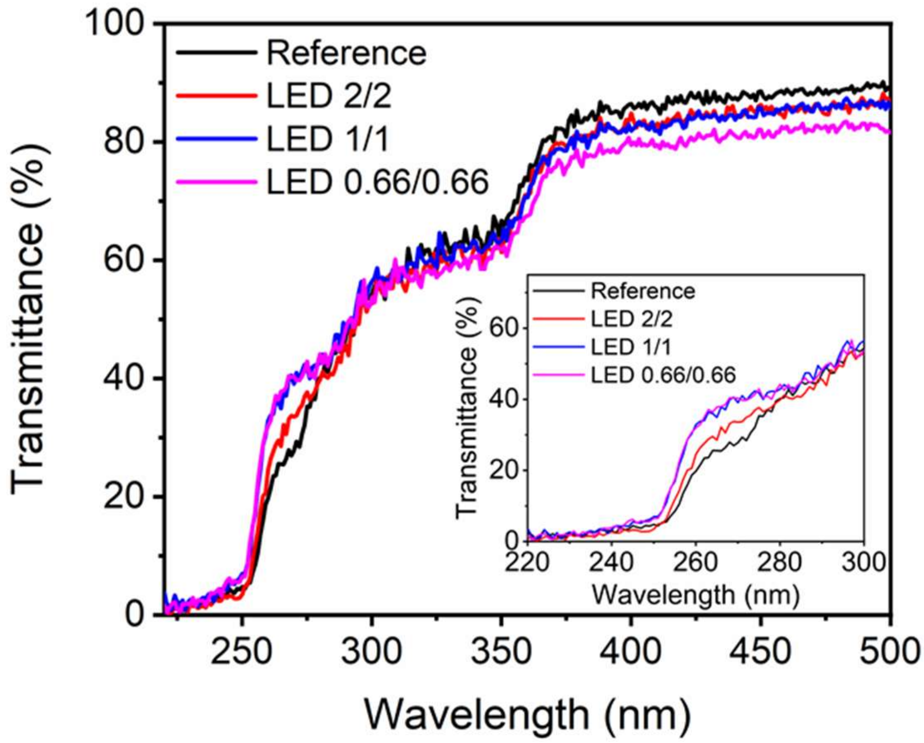

Figure 4. Transmittance of DUV LEDs with different p-AlGaN/AlGaN SLs. The inset of Figure 4 presents transmittance of these DUV LEDs within the wavelength range of 220–300 nm.

4. Conclusions

We replaced the p-$Al_{0.48}Ga_{0.52}N$ hole injection layer with p-$Al_{0.8}Ga_{0.2}N/Al_{0.48}Ga_{0.52}N$ SLs to enhance the light output power of DUV LEDs. The period thickness of the p-$Al_{0.8}Ga_{0.2}N/Al_{0.48}Ga_{0.52}N$ SLs affected the performances of the DUV LEDs. We found that the DUV LED with the 5-pair $Al_{0.8}Ga_{0.2}N$ (2 nm)/$Al_{0.48}Ga_{0.52}N$ (2 nm) SL structure showed increased V_f and reduced light output power compared with the reference LEDs. The SL structure could improve the performances of the DUV LEDs when its period thickness was reduced to less than 4 nm. Therefore, in this study, the DUV LEDs with the 10-pair $Al_{0.8}Ga_{0.2}N$ (1 nm)/$Al_{0.48}Ga_{0.52}N$ (1 nm) SL presented V_f reduction of 0.23 V and light output power improvement of 15% at a current of 350 mA. The improved light output power of the DUV LEDs could be attributed to the enhancement in hole injection by the 10-pair $Al_{0.8}Ga_{0.2}N$ (1 nm)/$Al_{0.48}Ga_{0.52}N$ (1 nm) SL. Moreover, the 10-pair SL could slightly suppress the Auger recombination and current overflow of the DUV LEDs in the high-current operation region due to better current spreading. However, the enhancement in light output power was reduced to 4.3% when the period thickness of the p-$Al_{0.8}Ga_{0.2}N/Al_{0.48}Ga_{0.52}N$ SL structure was reduced to 1.32 nm (15-pair $Al_{0.8}Ga_{0.2}N$ [0.66 nm]/$Al_{0.48}Ga_{0.52}N$ [0.66 nm] SL). In addition to improved carrier injection, the DUV LEDs with the p-$Al_{0.8}Ga_{0.2}N/Al_{0.48}Ga_{0.52}N$ SL structure demonstrated reduced light absorption at the emission wavelength compared with the reference LEDs. Therefore, the DUV LEDs with p-$Al_{0.8}Ga_{0.2}N/Al_{0.48}Ga_{0.52}N$ SLs should have better light extraction efficiency than the reference LEDs. This phenomenon may also be ascribed to the enhancement in the light output of the DUV LEDs with the p-$Al_{0.8}Ga_{0.2}N/Al_{0.48}Ga_{0.52}N$ SL hole injection structure.

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Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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