GaN Free Graded Hole Source Layer Terminated Structure for Efficient AlGaN-based UV-C LED

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***Abstract*— In this simulation study, we replace the p-GaN and p-$Al_{0.65}Ga_{0.35}N$ layers with graded p-$Al_xGa_{1-x}N$ layer (x = 0.65−0) to improve the light extraction efficiency and internal quantum efficiency (IQE). This enhances the hole supply by varying the polarization charge density (also reduces the resistivity of the p-AlGaN layer), increases the hole concentration by ~2.5-fold in the final proposed structure, and enhances the radiative recombination rate in the active region. This increases the maximum IQE by ~49% in the final proposed structure.**

***Keywords*— p-AlGaN, p-GaN, IQE, LEE, UV-C.**

I. Introduction

The aluminium gallium nitride (AlGaN)-based ultraviolet (UV)-C light-emitting diodes (LEDs) have inherent advantageous properties, such as, nontoxic material composition, high durability, compactness, long lifespan, and low power consumption, that makes them ideal for a wide range of applications in disinfection, water purification, medicine, food processing, polymer curing, non-destructive inspection, spectroscopy and many more [1]. Thus, AlGaN is also a potential candidate for UV-C LEDs with properties such as a direct bandgap and high breakdown voltage [2]. AlGaN bandgap varies from 3.42 eV to 6.2 eV, which covers emissions from 200-365 nm [2].

The AlGaN-based UV-C LEDs still underperform due to the lower external quantum efficiency (EQE). The EQE of UV-C LEDs depends on the light extraction efficiency (LEE) and the internal quantum efficiency (IQE), *i.e.*, EQE = LEE × IQE [3]. The IQE is the measure of the number of photons emitted from the active region with respect to the number of charge carriers injected into the active region, and LEE is the measure of the number of photons emitted from the free space with respect to the number of charge carriers injected into the active region [4]. Due to its highly resistive nature, the ohmic contact of LEDs at the p-region cannot be fabricated directly onto the p-AlGaN layer [4]. Thus, the p-GaN layer serves as a contact layer at the p-side [4]. The holes of the p-GaN layer are restricted by the p-AlGaN barrier during the transport [4]. Also, the LEE is affected by the p-GaN layer as it absorbs most of the emitted light, less than 365 nm [4].

Thus, in this simulation study, we attempt to improve the LEE and IQE by replacing the p-GaN and p-$Al_{0.65}Ga_{0.35}N$ layers with a graded p-$Al_{0.65}Ga_{0.35}N$ layer (p-$Al_{0.65}Ga_{0.35}N$ to GaN). The simulation has been performed using the Advanced Physical Models of Semiconductor Devices (APSYS) crosslight software to characterize the same.

II. LED Structure and Parameters

Fig. 1 shows the reference LED structure (sample A) consisting of three regions, *i.e.*, p-*i*-n. The reference structure consists of the following epitaxial layers given in Table 1. In the proposed sample B, the p-GaN layer is removed in order to improve the LEE and IQE, whereas, in sample C, the p-

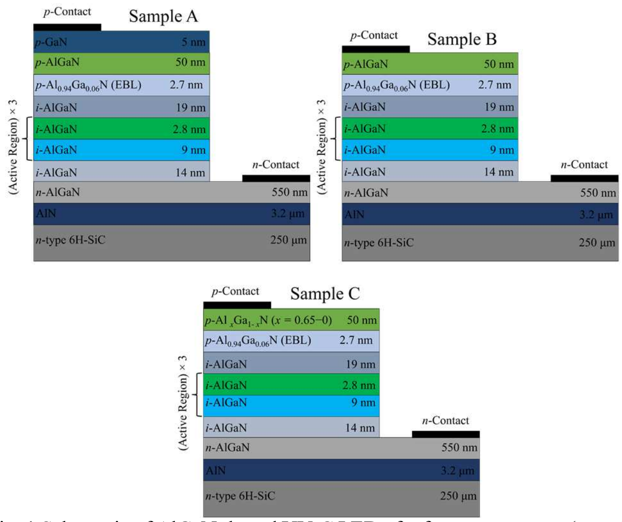

Fig. 1 Schematic of AlGaN- based UV-C LED of reference structure (sample A), sample B (without the p-GaN layer), and sample C (with graded p-AlGaN layer).

GaN and p-$Al_{0.65}Ga_{0.35}N$ layers are replaced with graded p-$Al_xGa_{1-x}N$ (x = 0.65−0) for improving the hole supply, the LEE, IQE and hence, the eternal quantum efficiency (EQE).

Table 1. Epitaxially grown AlGaN-based UV-C LEDs

S. No.	Epitaxial Layer	Thickness (nm)	Doping (cm^{-3})
1	p-GaN	5	2×10^{18}
2	p-$Al_{0.65}Ga_{0.35}N$	50	1×10^{17}
3	p-$Al_{0.94}Ga_{0.06}N$	2.7	1×10^{17}
4	*i*-$Al_{0.65}Ga_{0.35}N$	19	Undoped
5	*i*-$Al_{0.52}Ga_{0.48}N$	2.8	Undoped
6	*i*-$Al_{0.65}Ga_{0.35}N$	9	Undoped
7	*i*-$Al_{0.52}Ga_{0.48}N$	2.8	Undoped
8	*i*-$Al_{0.65}Ga_{0.35}N$	9	Undoped
9	*i*-$Al_{0.52}Ga_{0.48}N$	2.5	Undoped
10	*i*-$Al_{0.65}Ga_{0.35}N$	9	Undoped
11	*i*-$Al_{0.65}Ga_{0.35}N$	14	Undoped
12	n-$Al_{0.65}Ga_{0.35}N$	550	2×10^{18}

III. Results and Discussions

The LEE degradation due to the p-GaN layer is the primary issue in the AlGaN-based UV-C LEDs as it absorbs all the emitted light less than 365 nm [4]. Also, the highly resistive nature of the p-AlGaN layer restricts the direct fabrication of ohmic contact on the p-AlGaN layer [4]. Thus, to mitigate these issues, we introduce a simulation-based study by replacing the p-GaN and p-AlGaN layers with the graded p-AlGaN layer. First, we remove the p-GaN layer (sample B) from the reference sample to prevent the absorption of emitted light (less than 365 nm) from the active region to improve the LEE and IQE. Now, p-contact is made with the p-$Al_{0.65}Ga_{0.35}N$ layer, having a bandgap of ~4.99 eV,

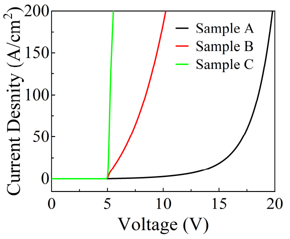

Fig. 2. I-V characteristics of samples A, B, and C. The reduced resistivity due to the graded p-AlGaN layer reduces the operating voltage in sample C by ~1/3 and ~1/2 compared to samples A and B, respectively.

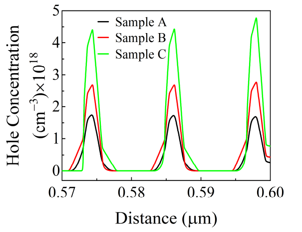

Fig. 3. Hole concentration of samples A, B, and C, respectively, at a current density of 0 to 200 A/cm^2. This figure displays the improvement of hole concentration by ~2.5-fold and ~1.5-fold compared to samples A and B, respectively.

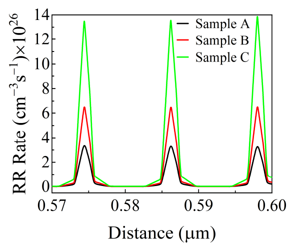

Fig. 4. RR rate of samples A, B, and C, respectively, at a current density of 200 A/cm^2. This figure demonstrates the improvement of the RR rate in sample C by ~4-fold and ~2-fold compared to samples A and B, respectively, at a current density of 200 A/cm^2. The improved hole concentration in the active region and reduced resistive losses enhance the RR rate in sample C.

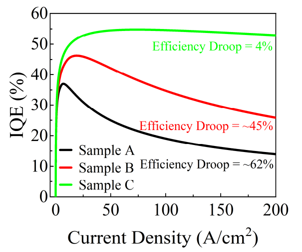

Fig. 5. IQE of samples A, B, and C, respectively, with varying current densities of 0 to 200 A/cm^2. This figure displays the improvement of maximum IQE by ~49% and ~24% in sample C compared to samples A, and B, respectively. The efficiency droop of sample C is restricted to a lower value of 4% compared to other samples.

rejecting the absorption of light ~276 nm (hν~4.49 eV, not shown) emitted from the active region. However, the highly resistive p-AlGaN layer has fewer holes, which further needs to be overcome by the high energy EBL (p-$Al_{0.94}Ga_{0.06}N$, hν~5.92 eV) [4]. The fewer holes at the p-$Al_{0.65}Ga_{0.35}N$ and the high energy EBL increase the operating voltages in samples A and B. But, in sample C, we replace the p-GaN and p-$Al_{0.65}Ga_{0.35}N$ with graded p-$Al_xGa_{1-x}N$ (x = 0.65−0) to improve LEE and IQE. Also, the advantage of performing grading from x = 0.65 ($Al_{0.65}Ga_{0.06}N$) to x = 0 (GaN) in the growth direction lies in indirectly restricting the direct fabrication of p-contact on the p-AlGaN layer. The variation of Al composition (x) in the graded p-$Al_xGa_{1-x}N$ layer varies the polarization charges, enabling the generation of holes in the p-AlGaN layer and reducing the resistivity of the p-AlGaN layer [5]. The reduction of resistivity reduces resistive losses and, hence, reduces the operating voltage in sample C, shown in Fig. 2. The operating voltage of samples A, B, and C are 19.8, 10.3, and 5.55 V, respectively. The operating voltage has been reduced by ~1/3 in sample C and ~1/2 in sample B compared to sample A. The holes generated by the variation in polarization improves the hole supply, which increases the hole concentration in the active region, as shown in Fig. 3. The hole concentration in the case of sample C (4.45×10^{18} cm^{-3}) is improved by ~2.5-fold compared to sample A (~1.8×10^{18} cm^{-3}), whereas the same for sample B is improved by ~1.5-fold compared to sample A at a current density of 200 A/cm^2. Thus, the reduced light absorption due to the removal of the p-GaN layer (improved LEE), lower resistive losses, and enhanced hole concentration improves the radiative recombination (RR) rate in the case of sample C (13.8×10^{26} cm^{-3}s^{-1}) by ~4-fold and ~2-fold compared to sample A (~2.65×10^{26} cm^{-3}s^{-1}), and B (~6.75×10^{26} cm^{-3}s^{-1}), respectively at a current density of 200 A/cm^2, depicted in Fig. 4. The enhanced RR rate increases the IQE in the case of sample C compared to other samples, shown in Fig. 5 at a varying current density 0 to 200 A/cm^2. The IQE and efficiency droop of samples A, B, and C are calculated using the following equations [3]

$$\eta_{IQE} = \frac{Bn}{A+Bn+Cn^2} \quad (1)$$

$$\text{Efficiency Droop (\%)} = \frac{\eta_{max} - \eta_{200A/cm^2}}{\eta_{max}} \times 100 \quad (2)$$

where A, B, C, n, η_{max}, η_{200/cm^2} are the SRH lifetime (in sec), RR coefficient (in cm^3/s), Auger coefficient (in cm^6/s), electron concentration, maximum IQE, and IQE at 200 A/cm^2, respectively. Thus, the maximum IQE of samples A, B, and C are ~37, ~46, and ~55%, respectively, at a varying current density of 0 to 200 A/cm^2. The maximum IQE of the proposed structure (sample C) is improved by ~49% and ~24% compared to samples A and B, respectively. The improvement in the IQE is due to the enhanced RR rate, which is further improved with reduced resistive losses and increased hole concentration in the active region. The efficiency droop is also restricted to a lower value in the case of sample C (4%) compared to samples A (~62%) and B (~45%), respectively. Thus, with this simulation study, we conclude that the final proposed structure is practically realizable for improving the performance parameters (RR rate, LEE, IQE, and hence the external quantum efficiency) of AlGaN-based UV-C LED.

IV. Conclusion

Replacing the p-GaN and p-$Al_{0.65}Ga_{0.35}N$ layers with graded p-$Al_xGa_{1-x}N$(x=0.65−0) reduces the resistive losses, enhances the hole concentration (by ~2.5-fold), which increases the RR rate (by 4-fold) in the final proposed structure. This improves the IQE of the final structure by ~49%. Also, the absence of the p-GaN layer is expected to cause improvement in the LEE of the final proposed structure.

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References

[1] A. Pandey, J. Gim, R. Hovden, and Z. Mi, “Electron overflow of AlGaN deep ultraviolet light emitting diodes,” *Appl Phys Lett*, vol. 118, no. 24, Jun. 2021, doi: 10.1063/5.0055326.

[2] B. Choubey and K. Ghosh, “Effect of Highly Doped p-AlGaN Layer to Improve the Ultimate Performance Parameters of 275 nm AlGaN-based UV-C LED,” in *IEEE Electron Devices Technology and Manufacturing Conference: Strengthening the Globalization in Semiconductors, EDTM 2024*, Institute of Electrical and Electronics Engineers Inc., 2024. doi: 10.1109/EDTM58488.2024.10512175.

[3] J. Piprek, “Efficiency droop in nitride-based light-emitting diodes,” *Physica Status Solidi (A) Applications and Materials Science*, vol. 207, no. 10, pp. 2217–2225, Oct. 2010, doi: 10.1002/pssa.201026149.

[4] J. Yan *et al.*, “Improved performance of UV-LED by p-AlGaN with graded composition,” *Physica Status Solidi (C) Current Topics in Solid State Physics*, vol. 8, no. 2, pp. 461–463, Feb. 2011, doi: 10.1002/pssc.201000458.

[5] S. J. Cho *et al.*, “P-type silicon as hole supplier for nitride-based UVC LEDs,” *New J Phys*, vol. 21, no. 2, p. 023011, Feb. 2019, doi: 10.1088/1367-2630/ab0445.