

necessarily decrease with scaling. For example, Yu et al. [12] investigated the size-dependent characteristics of DUV LEDs, achieving a 20% increase in EQE when the LED diameter is reduced from 300 μm to 20 μm . This revealed that smaller mesa areas can deliver higher LOP and uniform current spreading. The research group further verified that the EQE could be improved by inclining the chip sidewall, which is more effective in μLEDs with a 20–40 μm scale. Owing to their small areas and small junction capacitance, DUV μLEDs can be operated at high current densities and exhibit a high modulation bandwidth, which is an available light source for high-speed UV communication. Similarly, as my simulation of the scale effect on DUV LED IQE shown below, as the LED size $L_1:L_2$ scaled down from 120 $\mu\text{m}:20\mu\text{m}$ to 6 $\mu\text{m}:1\mu\text{m}$, the IQE of the LEDs didn't strictly decrease with the decrease of the scale. Though the smallest scale, 6 $\mu\text{m}:1\mu\text{m}$, did exhibit lowest IQE, other LEDs with small scales, such as the one with the size of 12 $\mu\text{m}:2\mu\text{m}$, still have an IQE that is comparable to that of the largest scaled LED. Therefore, we can still achieve a decent internal quantum efficiency (~ 0.9) with a scale size of a few microns, which is the typical size for the DUV micro-LED to be used in environmental monitoring and medical equipment.

In addition, there are other methods can be used to mitigate the decrease of IQE as the decreased LED size, such as improving crystal quality and passivating the surface of the LED. However, because of the time limit of the project, I didn't have time to explore these thoughts.

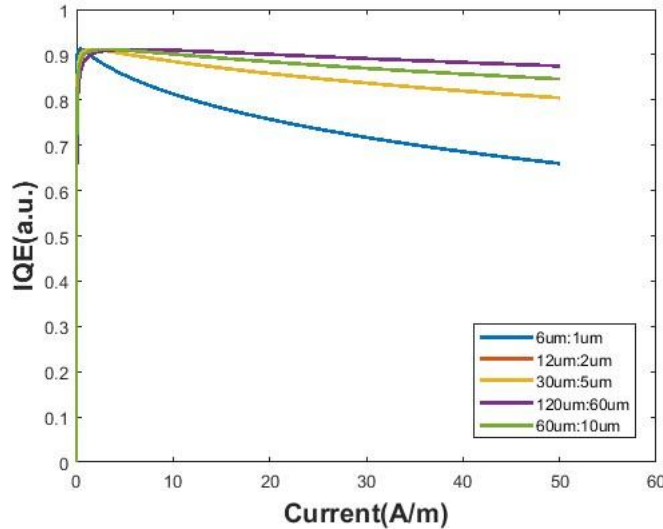


Fig. 11 Scale effect on IQE of DUV LED

Conclusion

AlGaIn-based materials have exhibited considerable potential for fabricating ultraviolet (UV) light-emitting diodes (LEDs) owing to their direct, wide, and adjustable energy bandgap. AlGaIn-based devices have extensive applicability owing to their stable physico-chemical properties. With decades of research effort, significant progress has been achieved in enhancing the working efficiency of AlGaIn-based LEDs by optimizing the crystalline quality, doping efficiency, and device design. However, a DUV LED with high IQE is still hard to achieve because highly efficient p-type doping of AlGaIn layers is difficult to achieve; the large difference in electron mobility and hole mobility in AlGaIn-based materials increases the difficulty of fabricating devices with high injection efficiency for electrons and holes simultaneously; the quantum-confined Stark effect (QCSE) reduces the probability of radiative recombination between electrons and holes; the scale effect on LED increases the non-radiative recombination rate; and the extremely low light extraction efficiency further decreases the external quantum efficiency (EQE) of

AlGaN-based LEDs. In order to tackle those challenges and increase the efficiency of the DUV LED, in this project, I simulated several methods with calibrated layer composition and structure.

First, the Al composition in quantum well plays an important role in determining the LED efficiency because the Al composition affects the electron and hole confinement in the QW layer, which can affect the LED's efficiency and output power. According to my simulation, the IQE slightly increased as I increased the Al composition from 0.6 to 0.82 for the $\text{Al}_x\text{GaN}/\text{AlN}$ MQW structure. However, if the Al composition is too high, the electrons and holes may become trapped in defects or dislocations in the crystal structure, which can reduce the LED's efficiency. In addition, from the simulation we can see that the increase of the IQE became less significant as we further increased the Al composition. Therefore, we shouldn't make the Al composition as high as possible if we want to design a good UVC LED. Instead, compromise must be made to other parameters.

Second, in order to against the spatial separation of wave functions in quantum-confined Stark effect (QCSE) and increase the LED efficiency, I used an alternative MQW structure with binary ultrathin GaN/AlN, and the thickness of the GaN wells versus the AlN barriers was 1ML:4ML in order to keep the similar composition as the control $\text{Al}_{0.8}\text{GaN}$ sample. According to the literature, this would give me a higher IQE because it increases the transition energy between the conduction and valence bands and the radiative recombination probability should also increase. However, because of the difficulty in reproducing the structure in Crosslight. The simulation went wrong, and I only ended up getting an IQE of ~20%.

Third, the doping efficiency of the p-type is the key factor for improving the internal quantum efficiency and decreasing the forward voltage because the high carrier concentration in the AlGaN layers not only produces a low resistance, but also guarantees great ohmic contact with the electrodes. Thus, the working voltage of DUV-LEDs is minimized, which results in lower thermal losses as well as a higher wall-plug efficiency and device reliability. In addition, light extraction efficiency is also a big concern for the IQE when designing a UV LED. For LEDs operating in the deep-ultraviolet (DUV) region (≤ 280 nm), the LEE is generally $<10\%$ because the top p-GaN contact layer can absorb considerable light owing to its relatively narrow bandgap. Therefore, in my project, I design a p-type $\text{Al}_x\text{GaN}/\text{undoped GaN}$ superlattice (SL) structure to replace the p-GaN contact. Though the IQE increased as the composition x changed from 0 to 0.4, the internal resistance got worse quickly as it changed from 0.3 to 0.4. Therefore, depending on the application, $\text{Al}_{0.4}\text{GaN}/\text{GaN}$ may not be the optimal choice.

Finally, because some applications such as sterilization of medical equipment and environmental monitoring require a DUV LED of a size in a few microns, the scaling effect on DUV LED must be studied. Unlike micro-LED that will have decreased IQE as the scale decreases due to increased surface recombination and non-radiative recombination originating from defects and impurities, the DUV μLEDs can improve the efficiency owing to the relaxation of strain, enhancement of LEE, and mitigation of the severe current crowding effect. In my project, I simulated my DUV LED structure with various scales of $L_1:L_2$. It turned out the IQE didn't strictly decrease with the decreasing scale. Though small scales, such as $L_1:L_2=12\mu\text{m}:2\mu\text{m}$, still have smaller IQE compared to large scales, such as $L_1:L_2=120\mu\text{m}:20\mu\text{m}$. The decrease in IQE is already very small (within 3%).

There are also several ways to further improve my work. First, more simulations and studies can be done with the ultrathin GaN/AlN QW structure to check whether it can really give a boost on the IQE. Second, as for the scaling effect on IQE of the DUV LED, more parameters can be included to the structure during the simulation such as the surface recombination and surface passivation. Detailed simulation on Auger, radiative and Shockley-Read-Hall recombination can also be included to have a better understanding of the contributions from each component in the ABC model. Finally, the effect of donor doping level can also be considered because with the increase in Al composition, n-type dopant Si tends to relax from the

donor state to an acceptor-like DX center, resulting in a dramatic increase in donor ionization energy thus a decrease in n-type doping level. Because the donor doping level is closely related to the internal resistance and IQE of the DUV LED, the topic is worth exploring if we want to further increase the LED efficiency.

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