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# P-epitaxial Layer Thickness and P-side Metal Reflection on the Luminous Power of Deep Ultraviolet LED

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***Abstract*—In this study, deep ultraviolet (DUV) LEDs with 280 nm emission wavelength were successfully fabricated on 3-inch (1000) substrates using plasma-assisted molecular beam epitaxy (PAMBE) system. To further enhance the light extract efficiency of the DUV LEDs, the effects of the thickness of the p-type epitaxial layer and the material of the p-side metal reflector on the light output power of the flip-chip DUV LEDs were deeply investigated. Firstly, through an optical resonance model, we determined that the LED structures output light intensity is higher when the thickness of the p-type epitaxial layer is 0.45-0.5 times the emission wavelength. Experimental analysis confirmed that when the p-type epitaxial layer thickness is 0.49 times the emission wavelength, the light output power of the 280 nm DUV LED reaches approximately 6 mW. This experimental result is in complete agreement with the theoretical simulation. Secondly, furthermore, the study increased the direct contact area ratio of aluminum on the p-type GaN surface to 75% using a nickel/aluminum contact metal grid method. This grid metal contact method not only retains the good ohmic contact between nickel and p-type GaN but also enhances the reflectivity of DUV light at the p-type GaN and contact metal interface. Ultimately, this increased the light output power of the 280 nm DUV LED to approximately 8 mW.**

***Keywords: Deep-ultraviolet light emitting diodes, Molecular beam epitaxy, metal reflector, Gallium Nitride***

## I. INTRODUCTION

In recent years, new types of ultraviolet (UV) light sources represented by AlGaN-based flip-chip DUV light-emitting diodes (LEDs) have garnered extensive attention due to their profound applications in water purification [1], biosensing [2], and cleaning and disinfection [3,4]. However, efficient DUV light sources remain relatively scarce [5] due to constraints in DUV light extraction efficiency. The light extraction efficiency based on AlGaN quantum wells (QWs) is only about 10% [6,7], severely limiting the luminous power of such DUV LEDs. Factors affecting light extraction efficiency include not only epitaxial defects in AlGaN materials but also structural design constraints:

The optical resonance cavity effect formed by the p-type epitaxial layer (including the p-type electron blocking layer, p-type AlGaN layer, and p-type GaN hole injection layers) and the p-type GaN top contact metal. In this resonance effect, the thickness of the p-type epitaxial layer influences optical resonance. The total internal reflection effect in the LED structure causes strong photon confinement, allowing only a very small amount of light to escape through the escape cone to the outside of the device, while the rest is trapped within the epitaxial layer, resulting in low output power.

The top p-type GaN layer exhibits strong absorption of DUV light. In previous work, the thickness of the p-type GaN layer typically exceeded 100 nm [8], significantly reducing the output of DUV light. Thinning the p-type GaN layer can effectively reduce DUV optical losses. Overall, the thickness of the p-type epitaxial layer plays a crucial role in light interference, light intensity distribution, radiation patterns, and the luminous intensity of the LED. Therefore, optimizing the thickness of the p-type epitaxial layer is essential.

Different p-type GaN top contact metal materials exhibit varying absorption (reflection) effects on DUV light, and the luminous intensity of flip-chip DUV LEDs is highly dependent on this reflection. Typically, metals are more efficient and economical choices than photonic crystals or distributed Bragg reflectors. Among various metals, aluminum is the most ideal reflective material for DUV light due to its high reflectivity of over 90% in the DUV region [9]. However, due to aluminum's low work function [10], it is difficult to form good ohmic contacts on p-type GaN or high aluminum content p-type AlGaN. Therefore, researchers often insert a very thin nickel layer into the aluminum-based reflective electrode to form a better ohmic contact and reduce contact resistance. However, this method inevitably increases the absorption of DUV light by the electrode contact layer and reduces the reflection effect at the interface while lowering resistance and voltage. Currently, research on p-type thickness optimization [11] and top contact reflection [12,13] is relatively limited. Therefore, based on previous research, it is urgent to design a p-type contact electrode with high reflectivity and good ohmic


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contact, which is of great significance for improving the light extraction efficiency of DUV LEDs.

Given this context, this paper employs theoretical simulation and experimental research to discuss, step by step, the effects of two designs the thickness of the p-type epitaxial layer and the nickel/aluminum meshed contact metal on the optical power of DUV LEDs, aiming to identify the optimal conditions. Finally, by combining these two designs, we investigate their impact on the luminous intensity of DUV LEDs, with the goal of maximizing the optical power of DUV LEDs.

## II. DESIGN AND SIMULATION

As illustrated in Schematic Diagram 1, this study employs a plasma-assisted molecular beam epitaxy (PAMBE) system to grow DUV LED structures on a 3-inch C-plane (0001) sapphire substrate. Along the epitaxial growth direction, the main epitaxial layers include: an n-type AlGaN layer with electron transport properties, a multi-quantum well (MQW) active layer, and a p-type epitaxial layer with hole transport properties. The p-type epitaxial layer is further composed of a p-type electron blocking layer (p-EBL), a low aluminum-content p-type AlGaN layer, and a p-type GaN layer. The metal stack layer on the p-type epitaxial side can be deposited on the p-type GaN surface via an electron beam evaporation system. Along the epitaxial direction, this metal stack layer consists of alternating layers of nickel and aluminum, with nickel serving as the direct contact metal.In this study, to maximize the luminous efficiency of the LED, our experimental design is as follows: 1. Using the metal stack layer interface as a metal reflector, we adjust the thickness of the p-type epitaxial layer with hole transport properties (expressed as a multiple of the active region emission wavelength $\lambda_n$) to seek the optimal thickness combination, thereby enabling constructive interference of DUV light within this optical path. 2. Optimizing the material of the metal reflector from the first design. Specifically, under the premise of maintaining nickel as the contact metal and the total metal contact area unchanged, we uniformly insert a meshed structure to appropriately reduce the direct contact area of nickel and increase the direct contact area of aluminum. This method aims to enhance the reflector's ability to reflect DUV light, thereby improving the backside light extraction efficiency.

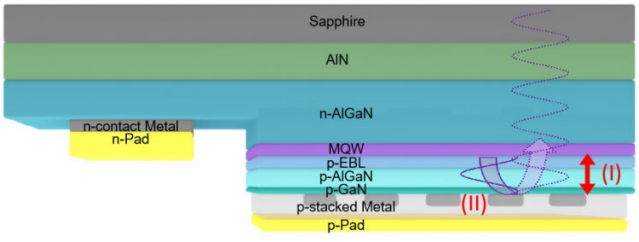


Figure 1. Structure diagram of inverted DUV LED. Where (I) represents the P-type epitaxial layer region and (II) represents the gridded P-side metal stack.

As mentioned above, when the optical path between the contact metal reflector and the quantum wells, as well as the wavelength of the DUV light emitted by the quantum wells, are on the same order of magnitude, the principles of the optical resonance cavity apply to this model. Therefore, we can use the following formula to simulate the entire process of optical resonance [8,14,15]:

$$|E|^2 = W_0^2 + W_r^2 + 2W_o\ W_r\ \cos(\pi + \theta + \theta^O)$$

Where $W_0$ and $W_r$ represent the amplitudes of the emitted light and reflected light, respectively, θ is the phase shift of the reflected light, and $\theta^O$ is a correction factor introduced due to variations in the thickness of the p-type epitaxial layer. Its expression is given by:

$$\theta O = 2\pi \frac{\Delta x}{\lambda_n} = 2\pi \frac{2d.\cos\emptyset}{\lambda_n}$$

Where $\lambda_n$ is the emission wavelength, n is the refractive index, d is the thickness of the p-type epitaxial layer, and Ø is the optical constant of the metal. Figure 2(a) provides a schematic representation of this simulation. As the DUV light emitted from the quantum well active layer propagates upward to the top metal reflector and is reflected downward, due to the varying thickness of the p-type epitaxial layer, two main characteristics emerge as shown in Figure 2(a): constructive and destructive interference. Figure 2(b) presents the calculation results of this study. From the graph, it can be deduced that as the thickness of the p-type epitaxial layer changes, the coherent light intensity on the side of the quantum well active region oscillates with the thickness of the p-type epitaxial layer. At 0.25 and 0.75 times the emission wavelength, the coherent light intensity on the side of the quantum well active region is weakest, while at a thickness of 0.45-0.5 times the emission wavelength, the coherent light intensity on the side of the quantum well active region is about five times that in the destructive interference case. According to these optical simulation results, we can conclude that if the emission wavelength of the quantum well active region is around 280 nm, the total thickness of the p-type epitaxial layer should ideally be controlled between 126-140 nm.

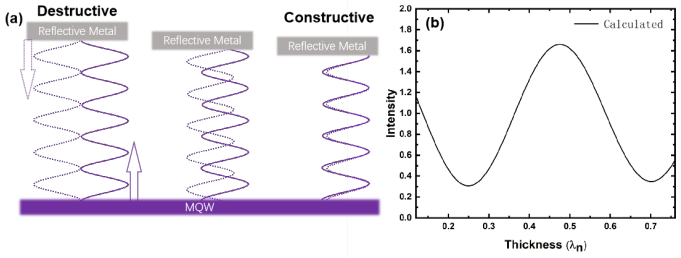


Figure 2. (a) A typical optical coherence diagram in the optical cavity model, (b) Theoretical simulation results of the variation of luminescence intensity with P-type epitaxial layer thickness (expressed as a multiple of laser wavelength n).

## III. RESULTS AND DISCUSSION

As shown in Figure 1, we successfully grew six sets of LED structures on a 3-inch sapphire (0001) substrate, with the thicknesses of the p-type epitaxial layers sequentially set at $0.18\lambda_n$, $0.28\lambda_n$, $0.39\lambda_n$, $0.49\lambda_n$, $0.6\lambda_n$, and $0.7\lambda_n$ nm. The emission peak wavelength of the quantum wells in this set of LEDs is approximately λn = 280 nm. Figure 3 shows the SEM cross-sectional image of the LED structure with a p-type epitaxial layer thickness of $0.49\lambda_n$ = 137 nm. From the image


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contrast, it is evident that the total thickness of the p-type epitaxial layer is generally below 200 nm.

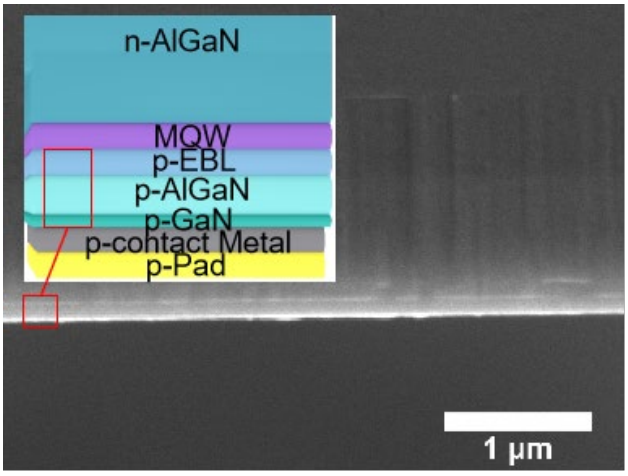


Figure 3. SEM cross-section of the flip-mounted LED structure, indicating the P-type epitaxial layer area.

Figure 4 presents the output power and theoretical calculated output light intensity of six sets of epitaxially grown LEDs with different p-type epitaxial layer thicknesses. The optical output power of the epitaxially grown LEDs oscillates with the variation in p-type epitaxial layer thickness, a result that aligns closely with the oscillation characteristics of the simulation. The LED with a p-type epitaxial layer thickness of 137 nm exhibits an optical output power as high as 6 mW, while the LED with a p-type epitaxial layer thickness of $0.7\lambda_n$ = 196 nm has an output power of only about 3 mW. This set of experiments demonstrates that a two-fold difference in output optical power can be achieved by adjusting the p-type epitaxial layer thickness. The experiments confirm that the optical reflection characteristics of the DUV LED quantum well emission between the quantum well and the p-side metal reflector conform to the optical resonance effect, and that the maximum output optical power can be achieved by designing the p-type epitaxial layer thickness to be around 137 nm. Additionally, in this experiment, the metal reflector on the p-side Ni, which has a reflectivity of only 53% for 280 nm DUV light, while aluminum has a reflectivity as high as 90% for the same wavelength. Next, under the premise of the optimal p-type epitaxial layer thickness, we attempt to adjust the metal reflector material to further enhance the output optical power.

In the experiment to improve the material of the metal reflector, this study designed the following scheme: using a meshed mask, we perform grid-shaped evaporation of nickel on the top of the p-type GaN, and then evaporate aluminum in the square openings of the grid, allowing direct contact between aluminum and p-type GaN. This design ensures excellent ohmic contact between nickel and p-type GaN while leveraging aluminum's superior reflectivity for DUV light to enhance the reflectivity of the p-side metal reflector. In the inset of Figure 5, we designed three combinations of nickel/aluminum meshed metal contacts, i.e., on the basis of 100% nickel contact with p-type GaN, while maintaining the effective metal contact area unchanged, appropriately reducing the effective nickel contact area by 25%-75%, and supplementing the reduced contact area with evaporated aluminum. Therefore, in Figure 5(a), through the nickel/aluminum meshing, the direct contact area of aluminum gradually increases from 0% to 75%. It is worth noting that when the nickel contact area ratio is below 25% (i.e., the direct contact area ratio of aluminum is above 75%), the current density of the p-type metal electrode becomes too high, causing excessive heating and damaging the electrical transport of the LED. For experimental comparison, we also prepared a full aluminum evaporation layer directly contacting p-type GaN, i.e., 100% aluminum contact. Figure 5 shows the reflectivity of the above-discussed five contact combinations as reflectors in the 200-400 nm wavelength range. It can be seen that the full nickel contact (0%) has the lowest reflectivity for ultraviolet light, and as the proportion of direct contact area of aluminum in the meshing increases, the reflectivity significantly rises, reaching as high as 90% for full aluminum contact (100%). This method can achieve good ohmic contact at the p-type GaN interface and significantly enhance the high reflectivity of DUV light at the interface, thereby optimizing light extraction efficiency.

If the resonant cavity model design in Figure 3 and the nickel/aluminum meshed contact metal design in Figure 5 are applied to DUV LEDs, it can not only enhance the high reflectivity of DUV light at the p-type GaN and metal reflector interface but also enable constructive interference between the reflected and emitted light, thereby maximizing light extraction efficiency. Figure 6(a) shows the optical power of LED structures with different nickel/aluminum meshed reflectors and different p-type epitaxial layer thicknesses. From the graph, it can be seen that when the thickness of the p-type epitaxial layer is between $0.39\lambda_n$ - $0.6\lambda_n$ nm, as the proportion of aluminum contact area in the nickel/aluminum meshed reflector increases, the optical power of the LED continues to rise. When the proportion of aluminum contact area in the nickel/aluminum meshed reflector reaches 75%, the optical power is maximized. However, in LED structures with thicknesses of $0.18\lambda_n$, $0.28\lambda_n$, and $0.7\lambda_n$ nm, as the proportion of aluminum contact area in the nickel/aluminum meshed reflector increases, the output optical power shows a gradual decreasing trend. From Figure 6(b), it can be seen that at $0.18\lambda_n$, $0.28\lambda_n$, and $0.7\lambda_n$ nm, the reflected light is in a destructive interference state in the optical resonant cavity. As the proportion of aluminum contact area in the nickel/aluminum meshed reflector increases, the reflected light intensity gradually increases, and the stronger the destructive interference state, the weaker the light extraction, thus exhibiting a gradual decrease in optical power. Figure 6 reveals that in LEDs with an emission wavelength of around 280 nm, when the thickness of the p-type epitaxial layer is $0.49\lambda_n$ = 137 nm and the contact area of aluminum in the metal reflector reaches 75%, the optical power of the LED increases from 6 mW in Figure 4 to 8 mW.


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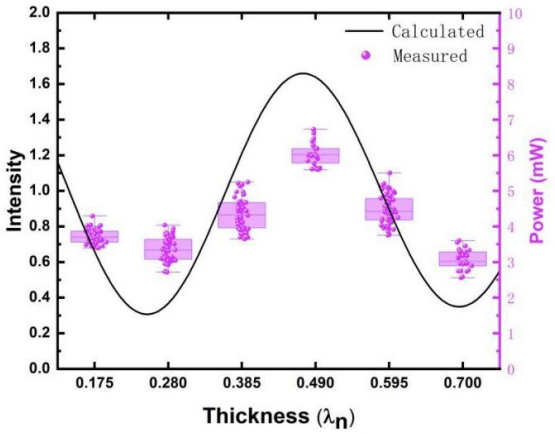


Figure 4. The output power and analog light intensity of the flip-mounted LED change with the thickness of the p-type epitaxial layer (a multiple of the laser wavelength n).

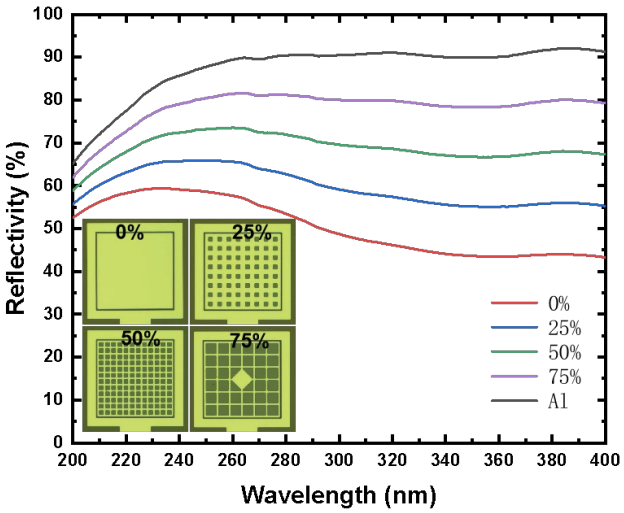


Figure 5. Spectral reflection of five metal contact modes in the 200 to 400 nm range. Illustration shows the metal electrode optical microscope layout of conventional LED (0%), where the square metal in the center is the P-plane contact metal area; Meshed nickel-aluminium metal optical microscope layout with 25% aluminum in direct contact with p-type GaN; The meshed nickel-aluminium metal optical microscope layout with 50% aluminum in direct contact with p-type GaN; Meshed nickel-aluminium metal optical microscope layout with 75% Al in direct contact with P-type GaN.

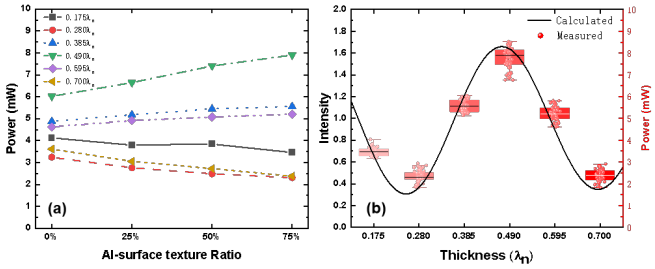


Figure 6. (a) The structural light power of LED with different p-type epitaxial layer thickness changes with the proportion of aluminum contact area of nickel-aluminum gridded contact layer; (b) Under the condition that the aluminum metal contact area ratio of the nickel-aluminum meshed contact layer is 75%, the output power and simulated light intensity of the flip-mounted LED change with the thickness of the p-type epitaxial layer (a multiple of the laser wavelength n).

## IV. CONCLUSION

Firstly, this paper employs an optical resonant cavity model to simulate the optical coherence process of DUV light between the quantum well and the p-type metal reflector. By continuously varying the thickness of the p-type epitaxial layer, the optimal thickness of around 137 nm was obtained under DUV light emission of around 280 nm. Experimental verification of this theoretical simulation showed that the LED's luminous power under constructive interference with a thickness of 137 nm was about 6 mW, which is twice that of the destructive interference LED's luminous power. Secondly, this study improved the traditional contact method of the p-type electrode metal by using a nickel/aluminum meshed contact method. Under the premise of maintaining the total contact area and ohmic contact with nickel, the optimal DUV light reflection effect was optimized by increasing the aluminum metal contact area. This method not only ensures ohmic contact between p-type GaN and the contact metal but also utilizes aluminum's high reflectivity for DUV light to enhance the constructive interference effect of light within the p-type epitaxial layer. Through five sets of experiments, it was found that when the proportion of direct contact area of aluminum is 75%, the LED's optical power reaches about 8 mW. This experimental design provides a new approach for achieving high light extraction efficiency in DUV LEDs.

## ACKNOWLEDGEMENTS

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