Study on the Degradation Performance of AlGaN-Based Deep Ultraviolet LEDs under Thermal and Electrical Stress

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Abstract: AlGaN-based deep-ultraviolet (DUV) LEDs could realize higher optical power output when adopting a p-AlGaN contact layer instead of a p-GaN contact layer. However, this new type DUV LEDs exhibit poor reliability. Thus, this study thoroughly investigates the degradation behaviors of AlGaN-based DUV LEDs with a p-AlGaN contact layer through different aging tests, including single thermal stress, single electrical stress with air-cooling, single electrical stress, and thermoelectric complex stress. It can be found that both high temperature and large working current play crucial roles in accelerating the degradation of optoelectronic properties of the DUV LEDs, and the single high thermal stress without electrical stress can also bring obvious performance degradation to the DUV LEDs, which is a significantly different finding from previous studies. This is because thermal stress on DUV LED could bring some metal electrode elements entering the p-AlGaN layer. Thus, the degradation of optical and electrical properties under the thermal and electrical stress could not be only attributed to the degradation of the device’s ohmic contacts, but also due to the metal electrode elements entering the p-AlGaN layer through thermal diffusion, leading to the generation of tunneling current and the generation of defects within or around the active region. Despite that the peak wavelengths of the DUV LEDs remained stable, the turn-on voltage and series resistance increased. Particularly worth mentioning is that the value of the optical power degradation under thermoelectric conditions is larger than the sum of the single thermal and single electrical optical power degradation, which is a result of the mutual reinforcement of thermal and electrical stresses to exacerbate the defect generation and ohmic contact degradation. Based on the study above, preparing p-AlGaN layers with hyperfine gradient aluminum fractions and reducing the junction temperature may help to improve the reliability of AlGaN-based DUV LEDs with the p-AlGaN contact layer.

Keywords: AlGaN-based DUV LED; thermal stress; electrical stress; degradation; reliability

1. Introduction

AlGaN-based DUV LEDs (wavelength from 200 to 280 nm) have developed into a crucial research area, attracting substantial international attention in recent years. Compared with traditional UV light-emitting lamps, AlGaN-based DUV LEDs have incomparable advantages, which include environmental friendliness, tunable emission wavelength, compact size, low power consumption, and so on [1–3]. Therefore, AlGaN-based DUV LEDs exhibit tremendous potential in many areas, such as water treatment [4], air purification [5], and precision medicine [6]. However, DUV LEDs have some disadvantages, such as shorter lifetimes in an extreme field [7,8] and poorer reliability, which limit their large-scale application as well as the rapid industrialization of AlGaN-based DUV LED devices.

So far, some studies on the degradation mechanism of AlGaN-based DUV LEDs under thermal or electrical stresses have been reported. Zhanhong Ma [9] conducted the aging tests at 100 ºC and 85 ºC, respectively, with the working current of 20 mA for 150 h. It
could be obtained that current was the main factor in the degradation in LED performance. Yingzhe Wang [10] reported aging tests at 91 °C with a working current of 50 mA for 50 h. It could be determined that a single thermal stress has little effect on the electro-optical characteristics of the DUV LED. Pradip Dalapati [11] conducted aging tests at 60 mA constant current, and then it was found that a gradual degradation in optical power due to an increase in the Shockley–Read–Hall recombination and the generation of new point defects in the active region. Additionally, XueFeng Zheng [12] conducted aging tests at a 50 mA constant current, and then it could be determined that the increased leakage current after stress can be attributed to the generation of defects. Mengwei Su [13] conducted aging tests at a constant current of 20 mA, 40 mA, and 80 mA under ambient temperature for 24 h. They were able to conclude that the migration and diffusion of donor impurities and dislocations under the current flow could lead to the deterioration of the quantum well crystal quality and lead to the attenuation of optical power, finally. Lixia Zhao [14] conducted aging tests at a 20 mA constant current, and then it could be determined that the electro-migration of the contact metal may generate the current leakage channel, which degraded the optical power of the LEDs. Yijun Lu [15] conducted aging tests at a 100 mA constant current, and then it could be determined that the degradation of optical power under the electrical stress could be attributed to the generation of stress-induced defects increasing the non-radiative recombination. The past reports of aging tests only focused on the degradation mechanism of AlGaN-based DUV LEDs with p-GaN film as the p-type contact layer under electrical stress.

With the development growth technology of AlGaN-based DUV wafers, the p-AlGaN layer is selected as the p-type contact layer instead of the traditional p-GaN layers, aiming for higher UV transmission. Previously, the device life was only about a few hundred hours. With the improvement in epitaxial layer growth process and chip preparation process, the lifetime of DUV LEDs has been improved to about 5000–10,000 h. The previous reports of the degradation mechanism are no longer applicable to the newest failure mechanism analysis. However, fewer degradation studies have been put forward for DUV LEDs with a p-AlGaN contact layer. In addition to that, the degradation mechanism of DUV LEDs is mainly investigated using constant electric stress aging tests. However, research on the systematic analysis and comparisons between the degradation mechanism of AlGaN-based DUV LEDs under single thermal, single electrical, and thermoelectric composite stress conditions are also relatively scarce. Therefore, it is very necessary to investigate the degradation of AlGaN-based DUV LEDs with p-AlGaN films as the p-type contact layer.

This study considers the degradation mechanism study of the AlGaN-based DUV LEDs with p-AlGaN thin films as the p-type contact layer. Thus, this study conducts single thermal stress aging tests, single electrical stress with air-cooling aging tests, single electrical stress aging tests, and thermoelectric composite stress aging tests to systematically analyze and compare the effects of single thermal, single electric, and thermoelectric complex stress on the degradation of optoelectronic characteristics of AlGaN-based DUV LEDs. It will help to improve the reliability design of AlGaN-based DUV LEDs.

2. Experimental Details
2.1. The Heterostructures of AlGaN-Based DUV LEDs

In this study, we have designed an AlGaN-based deep ultraviolet (DUV) LED structure with a p-AlGaN film serving as the p-type contact layer. Figure 1 shows the 278 nm LED growth heterostructure. The structures were prepared using the metalorganic chemical vapor deposition (MOCVD) on the sapphire substrate. The basic (0001)-oriented LED structure consists of, top to bottom, a 15 nm p-Al0.5Ga0.5N layer, a 10 nm n-Al0.8Ga0.2N layer, a 2 nm Al0.6Ga0.4N layer, a 22 nm n-Al0.8Ga0.2N layer, five-period Al0.7Ga0.3N/Al0.5Ga0.5N (17 nm/3 nm) multiple quantum wells (MQW), a 1500 nm n-Al0.6Ga0.4N layer, a 1500 nm n-Al0.7Ga0.3N layer, and a 2300 nm AlN layer. Trimethyl-gallium (TMGa), trimethyl-aluminum (TMAI), and NH3 were used as the sources of Ga, Al, and N, respectively. For the n- and p-type dopants, we used Silane and cyclopentadienyl magnesium, respectively.
Finally, the Cr/Al/Ni/Au (30/80/40/80 nm) stacks were deposited around the mesa as n-electrodes. The stacks were annealed utilizing a rapid thermal process at 630 °C for 7 min in an N2 ambient. The p-electrode comprised Ni/Au (20/50 nm) metal stacks and was annealed at 580 °C for 7 min in an N2 ambient.

![Diagram of DUV LED layer structure](image)

**Figure 1.** Schematic illustration of the DUV LED layer structure.

### 2.2. Sample Preparation and the Design of Aging Tests

The chips with the size of 250 × 450 (µm²) are based on flip-chip processing technology. Single chip is flip-chip mounted on an AlN sub-mount using gold tin alloy soldering. Finally, a batch of ten DUV LEDs were soldered onto a PCB. To investigate the failure mechanisms under thermal and electrical stresses on AlGaN-based DUV LEDs, a series of aging tests were conducted, including single thermal stress aging tests (A), single electrical stress with air-cooling aging tests (B), single electrical stress aging tests (C), and thermoelectric complex stress aging tests (D). The aging tests are shown in Table 1. A constant current was applied to the DUV LED aging samples on the PCB board with the LED-4005 current source. The temperature of different aging tests was provided using high and low temperature test chambers. The cooling methods for different aging test samples included natural cooling and air-cooling. Natural cooling is the natural heat exchange between the heat generated using the DUV LEDs and the environment. Air-cooling is the convective heat transfer between the heat generated using the DUV LEDs and the environment under the operation of the fan. To investigate the associated failure mechanisms, the optical, electrical, and thermal properties of the AlGaN-based DUV LEDs before and after the aging tests were measured using different analysis technologies. The electroluminescence, optical power, and forward voltage were collected automatically using a UV LED/Module radiation test system. Current-voltage (I–V) characteristics were measured using a semiconductor parameter analyzer. The case temperature of the DUV LEDs was measured using a thermocouple. The thermal resistance of the DUV LEDs was measured using a T3ster with heat current of 40 mA and sense current of 1 mA. All the aging tests were carried out for 1000 h. The photoelectric parameters of the DUV LED were measured at a current of 40 mA when naturally cooled to room temperature.

### Table 1. The plan of the aging tests.

<table>
<thead>
<tr>
<th>Aging Test</th>
<th>Aging Temperature (°C)</th>
<th>Aging Current (mA)</th>
<th>Cooling Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samples A</td>
<td>85</td>
<td>0</td>
<td>Natural cooling</td>
</tr>
<tr>
<td>Samples B</td>
<td>25</td>
<td>80</td>
<td>Air-cooling</td>
</tr>
<tr>
<td>Samples C</td>
<td>25</td>
<td>80</td>
<td>Natural cooling</td>
</tr>
<tr>
<td>Samples D</td>
<td>85</td>
<td>80</td>
<td>Natural cooling</td>
</tr>
</tbody>
</table>
3. Results and Discussion

3.1. Optical Properties

Figure 2 shows the optical power (a) and normalized optical power (b) of the DUV LEDs measured at 40 mA before and after the aging tests. It could be determined that the optical power of sample A decayed by 7.9% under a single thermal stress, the optical power of sample C decayed by 10.2% under a single electrical stress, and the optical power of sample D decayed by 24.3% under a thermoelectric complex stress after 1000 h of aging tests. High temperature and current significantly impacted the AlGaN-based DUV LED optical power degradation. Furthermore, it could be obtained that the value of the optical power degradation under thermoelectric conditions is larger than the sum of the single thermal and electrical optical power degradation. The thermoelectric complex stress led to a more pronounced optical power degradation, indicating that DUV LED device’s performance was more severely damaged under the thermoelectric complex stress condition.

![Figure 2. The optical power (a) and normalized optical power (b) of the DUV LEDs during the aging period.](image)

Previous studies have shown that single thermal stress has little effect on the degradation of the optical power of AlGaN-based UVC LEDs with p-GaN as the contact layer [9,10]. However, for aging sample A, the degradation of the optical power of AlGaN-based UVC LEDs with p-AlGaN as the contact layer is significantly affected by thermal stress. The degradation may be attributed to the degradation of the ohmic contacts of the LEDs. A comparison of aging samples A and B shows that the degradation of optical power under a single thermal stress is faster than electrical stress with air-cooling, which further suggests that temperature is an essential influential factor in the degradation mechanism of this type of LEDs with p-AlGaN contact layer. It also could be found that the degradation curves of sample B and C can be divided into two stages according to the different behaviors, indicating their different potentially dominant failure mechanisms. The optical power of these DUV LEDs increase may be related to the increase in hole concentration in the p-AlGaN because of the activation of the dopant Mg, leading to enhanced carrier injection efficiency and improved radiation recombination efficiency [16]. The optical power degradation may be related to the abundance of defects or dislocations present in the active region or p-type doping. These defects are activated under electrical stress, and serve as non-radiative recombination centers [17,18]. The degradation is also related to the degradation of ohmic contacts. The degradation mechanism for optical power also applies to sample D.

Figure 3 shows the electroluminescence spectra of aging samples A, B, C, and D under different stress. After 1000 h of aging, the peak wavelength of samples A, B, C, and D did not drift, except for the degradation of the electroluminescence intensity. It suggests that single thermal stress, electrical stress, and thermoelectric complex stress did not result in significant changes in the Al component of the active region of the LEDs.
The leakage current at Table 2. DUV LED before and after the aging test. Table 2 lists the leakage current before and after

3.2. Electrical Properties

Figure 4 shows the I–V characteristics (semi-logarithmic scale) of the AlGaN-based DUV LED before and after the aging test. Table 2 lists the leakage current before and after the stress measured at −2 V and 2 V. After 1000 h of aging tests, the reverse leakage current of sample A decreased by 2.77 × 10^−11 A and the forward leakage current increased by 9.4 × 10^−10 A under the single thermal stress. The reverse leakage current of sample B increased by 3.729 × 10^−10 A and the forward leakage current increased by 1.27 × 10^−11 A under the single electrical stress with air-cooling. The reverse leakage current increased by 3.31 × 10^−10 A and the forward leakage current increased by 9.4 × 10^−10 A under the single electrical stress. The reverse leakage current increased by 7.41 × 10^−9 A and the forward leakage current increased by 5.9 × 10^−8 A under the thermoelectric complex stress. It can be concluded that under the thermoelectric complex stress, the leakage current increased significantly compared to the single thermal or single electrical stresses.

Table 2. The leakage current at −2 V and 2 V of the LED samples before and after the stress.

<table>
<thead>
<tr>
<th>Aging Test</th>
<th>Leakage Current at −2 V Bias (A)</th>
<th>Leakage Current at 2 V Bias (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 h</td>
<td>1000 h</td>
</tr>
<tr>
<td>Sample A</td>
<td>−1.35 × 10^−10</td>
<td>−1.073 × 10^−10</td>
</tr>
<tr>
<td>Sample B</td>
<td>−9.095 × 10^−11</td>
<td>−4.638 × 10^−10</td>
</tr>
<tr>
<td>Sample C</td>
<td>−5.275 × 10^−11</td>
<td>−3.838 × 10^−10</td>
</tr>
<tr>
<td>Sample D</td>
<td>−4.183 × 10^−11</td>
<td>−7.452 × 10^−9</td>
</tr>
</tbody>
</table>
In general, the reverse leakage current can be attributed to the parasitic leakage path of the carriers [19]. Reverse leakage current remains almost unchanged under single thermal stress, suggesting the generation of no new parasitic leakage channels. The reverse leakage current increased under the single electrical, single electrical with air-cooling, and thermoelectric complex stresses, indicating the generation of new leakage channels. It is attributed to the generation of point defects in or around the active region of the LED which assist in carrier tunneling and form parasitic leakage paths in the active region. The type of point defects is related to the diffusion of Mg and H atoms [20,21]. These defects can also form non-radiative recombination centers, reducing the efficiency of the radiative recombination and ultimately decreasing the LED’s optical power.

Table 2. The leakage current at \(-2\) V and 2 V of the LED samples before and after the stress.

<table>
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<tr>
<td>Sample D</td>
<td>4.183 × 10^{-11}</td>
<td>7.452 × 10^{-9}</td>
</tr>
</tbody>
</table>

Figure 4. I–V characteristics (semi-logarithmic scale) of the 278 nm ultraviolet LED measured before and after the aging tests. (a) Sample A; (b) sample B; (c) sample C; (d) sample D.

Usually, the forward leakage current can be attributed to the defect-assisted tunneling process [22,23]. After 1000 h of aging tests, the forward leakage current of the single thermal stress, single electrical stress, and thermoelectric complex stress tests increased. However, the forward leakage current is almost unchanged under the single electrical stress with air-cooling. It shows that temperature is the key factor for the increase in the forward leakage current.

The increase in forward leakage current under single thermal stress may be attributed to the metal electrode elements entering the p-AlGaN layer through thermal diffusion, leading to the degradation of ohmic contacts and the generation of the tunneling current. For the single electrical stress, single electrical stress with air-cooling, and thermoelectric complex stress aging tests, the increase in the forward leakage current may be caused by the increase in defects in the active region, or else may be caused by the reduced activation
energy of the defects, or by the metal electrode elements entering the p-AlGaN layer through thermal diffusion. The increase in leakage current under thermoelectric complex stress is most significant, meaning a greater accumulation of defects and a reduction in the activation energy for these defects. The ideal factor, which is directly related to the depth of defect energy levels, serves as a crucial indicator for characterizing the rise in defects in AlGaN-based DUV LED materials. The formula for calculating the ideality factor [24] is represented as follows:

\[ n_{\text{ideal}} = \frac{q}{kT} \frac{\partial V}{\partial \ln I} \]  

(1)

where \( q \) is the unit charge, \( k \) is the boltzian constant, and \( T \) is the thermodynamic temperature.

We extracted the ideal factor from the low forward bias region of the I–V curve of the LEDs. The ideality factor variation of LED before and after aging are shown in Figure 5. The increase in the ideal factor of samples A, B, C, and D after 1000 h of aging tests may be ascribed to the generation of point defects within or around the active region, which are responsible both for trap-assisted tunneling (TAT) and non-radiative recombination [25,26]. The ideal factor is significantly increased under thermoelectric complex stress, which means that the defect generates more leakage current shunts and enhances the non-radiative recombination of carriers. Therefore, more energy is converted to heat, leading to a faster decrease in the optical power of the DUV LED.

![Figure 5. Ideality factor variation of AlGaN-based DUV LEDs before and after aging in various aging experiments.](image)

Figure 6 shows the I–V characteristic (linear coordinates) of the DUV LED after different aging tests for 1000 h. For samples A, B, C, and D, when powered with 6 V, the initial series resistances of single were 122 \( \Omega \), 121.6 \( \Omega \), 135.5 \( \Omega \), and 104.4 \( \Omega \), respectively, at before hours, and the series resistances increased to 130.5 \( \Omega \), 129.5 \( \Omega \), 163.3 \( \Omega \), and 138.4 \( \Omega \), respectively, after 1000 h. After 1000 h of aging tests, the turn-on voltage and the series resistance of all the LEDs increased. It shows that both the thermal and electrical stresses may accelerate the ohmic contact degradation of AlGaN-based LEDs.
initial series resistances were 122 Ω, 121.6 Ω, 135.5 Ω, and 104.4 Ω, respectively, at 0 h. After 1000 h of aging tests, the turn-on voltage and the series resistance of all the LEDs increased. It shows that both the thermal and electrical stresses may accelerate the ohmic contact degradation of AlGaN-based LEDs.

Figure 6. I–V characteristics (linear coordinates) of the 278 nm ultraviolet LED measured before and after the aging tests. (a) Sample A; (b) sample B; (c) sample C; (d) sample D.

3.3. Thermal Properties

For AlGaN-based LEDs, the thermal resistance and junction temperature are critical thermal performance parameters. The differential structure function can be calculated by the following formula [27]:

$$K(R_{th}) = \frac{dC_{th}}{dR_{th}} = c(x) \lambda(x) A^2(x)$$

(2)

where $c(x)$ is the volume heat capacity, $\lambda(x)$ is the thermal conductivity, and $A(x)$ is the cross-sectional area on the heat transfer path.

The specific thermal resistance of each package layer was plotted according to the differential structure function, as shown in Figure 7. Taking sample D as an example, $R_{Dj}$ is the thermal resistance of the chip, $R_d$ is the thermal resistance of the die attach, $R_{AlN}$ is the thermal resistance of the AlN ceramic substrate, $R_s$ is the thermal resistance of the solder paste, $R_{Al}$ is the thermal resistance of the aluminum substrate, and $R_t$ is the thermal resistance of the thermally conductive silicone grease. The thermal resistance of the unaged sample is 16.34 K/W. After 1000 h of aging tests, the thermal resistance of samples A, B, C, and D are 27.47 K/W, 25.88 K/W, 29.96 K/W, and 53.08 K/W. Based on the analysis above, the increase in the thermal resistance of the aged samples may be caused by the degradation of the ohmic contacts, the metal electrode elements entering the p-AlGaN layer through thermal diffusion, and the increase in defects in the active region.
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(a) (b)

Figure 7. The differential structure function of the LED samples before and after aging in different aging tests.

The formula for calculating the junction temperature is represented as follows [28]:

\[ T_j = T_c + V_F \times I_F \times R_{j-c} \]  \hspace{1em} (3)

where \( V_F \) is the forward voltage, \( I_F \) is the operating current, \( T_c \) is the case temperature, and \( R_{j-c} \) is the thermal resistance from the junction to the case.

The thermal resistance \( R_{j-c} \) of different aging samples from chip to case is extracted from the differential structure function of the LEDs, and the case temperature \( T_c \) of AlGaN-based DUV LEDs is measured using thermocouples, and the junction temperatures of samples B, C, and D are calculated by combining them with Equation (3). Figure 8a shows the variation curves of junction temperature of the different aging tests, and Figure 8b shows the junction temperature and the normalized optical power degradation percentage after 1000 h of aging tests. After 1000 h of aging tests, the \( R_{j-c} \) of samples A, B, C, and D are 12.02 K/W, 6.59 K/W, 12.95 K/W, and 41.32 K/W respectively, and the \( T_j \) of samples A, B, C, and D are 84.6 °C, 63.4 °C, 89.9 °C, and 139.2 °C, respectively. It can be obtained from Figures 7 and 8 that higher junction temperature of the LEDs led to more defects, a larger leakage current, and a faster degradation of optical power. Therefore, the optoelectronic performance and reliability of AlGaN-based DUV LEDs can be significantly improved by controlling the junction temperature of the LEDs during operation.

Figure 8. (a) Variation of junction temperature of LED samples with aging time in different aging tests. (b) Normalized optical power degradation rate and junction temperature of LED samples before and after aging in different aging tests.
4. Conclusions

In this study, we investigated the degradation mechanism of the AlGaN-based DUV LED with a p-AlGaN contact layer under thermal, electrical, and thermoelectric complex stress. We conducted a series of aging tests, including single thermal stress aging tests, single electrical stress with air-cooling aging tests, single electrical stress aging tests, and thermoelectric complex stress aging tests. The results indicate that both temperature and current are important factors affecting the photoelectric properties of the AlGaN-based DUV LED. After 1000 h of aging tests, the peak wavelength of AlGaN-based LED remains unchanged, while the turn-on voltage and series resistance increase. The degradation of optical and electrical properties under the thermal and electrical stress could be not only attributed to the degradation of the device’s ohmic contacts, but also due to the metal electrode elements entering the p-AlGaN layer through thermal diffusion, leading to the generation of tunneling current and the generation of defects within or around the active region. It can be obtained that a higher junction temperature in the LEDs led to more defects, a larger leakage of current, and a faster degradation in optical power. Therefore, the optoelectronic performance and reliability of AlGaN-based DUV LEDs with a p-AlGaN contact layer can be improved in the future by preparing p-AlGaN layers with gradient aluminum fractions and by controlling the junction temperature of the LEDs during operation. This work will provide a solid theoretical foundation for the preparation of AlGaN-based DUV LEDs with high optical power output.

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Conflicts of Interest: Author Jinmin Li is employed by the Shanxi Zhongke Lu’an Ultraviolet Optoelectronics Technology Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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