Analysis Of Degradation Effect on Deep-Ultraviolet Leds

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Abstract. Deep-ultraviolet light has a wide application range in daily life, such as the disinfection of water and surfaces of objects without any pollution. At the meanwhile, Light Emitting Diodes (LEDs) are fantastic light emitting devices with multiple advantages, such as high efficiency and relatively longer lifespan. Therefore, the invention of Deep-Ultraviolet LEDs (DUV-LEDs) is reasonable since it can make use of the advantages of LEDs for a lower cost in applications. However, not everything goes well with DUV-LEDs. Degradation greatly affects the performance and lifespan of DUV-LEDs. The efficiency and output power of DUV-LEDs would decrease dramatically after aging. In this passage, current, heat and defects are three main reasons of degradation and each of them are discussed in detail. The effect of degradation on I-V characteristics is included to present more detailed information. A newly developed manufactural method with graphene is mentioned, and suggestions and further research directions are provided to improve the lifespan and reliability of DUV-LEDs.

Keywords: Deep ultraviolet LEDs; Degradation; Performance; Graphene.

1. Introduction

LEDs are widely used in daily life of people today. To be a new generation of light emitting devices, its high efficiency and relatively longer lifespan are the greatest advantages which impress people and researchers the most. The need of a light source to emit deep ultraviolet light is essential and DUV-LEDs have gradually become a new option for people to use. Deep ultraviolet is very useful to people. Its special characteristic and high energy density can be applied in disinfection in many aspects, including water disinfection, surface disinfection, disinfection in hospitals, etc. At the meanwhile, the disinfection only requires to emit ultraviolet light into the water or on the surface of the object. This means the whole disinfection process would not bring in any source of pollution so that the original characteristic of liquid or object will be maintained after disinfection, unlike other methods of disinfection. However, the degradation of LEDs has become the main factor that affects the performance and the lifespan of LEDs. It has been confirmed that normal LEDs, which emit visible light, are greatly affected by degradation. Degradation can lead to the reduction of efficiency from the original to only 80% [1]. Considering the specialty of DUV-LEDs, the situation could impossibly be better.

This paper reviewed the basic mechanisms of degradation in DUV-LEDs, including the leakage current induced optical degradation and the generation of defects induced degradation. Then I focused on the key factors of degradation, including current, defects and heat. This paper has also included the aged I-V characteristics of DUV-LEDs, which proves that the effect of degradation is severe on DUV-LEDs. In the end, a new technology with graphene is discussed, which can help the manufacture of DUV-LEDs and probably extend the lifespan of the LEDs. Suggestions and expectations are also given for further research and analysis.

2. Basic Mechanisms of Degradation of Deep UV-LEDs

2.1. Leakage current induced optical degradation.

It has been discovered and confirmed that defects and current are two key factors in the degradation of Deep UV-LEDs (DUV-LEDs). At the meanwhile, defects and current are inevitable when any type of LEDs is applied in use. The effect of degradation on visible LEDs made by GaN has been explored and the conclusion is that even a minor current flowing through the LED can cause it to degrade. Situation could be more severe to DUV-LEDs. Researchers have studied the degradation of DUV-LEDs and explained the reasons of degradation.

In the past studies, the reasons accounts for the degradation are the migration of Al atoms from p-cladding, the generation of defects states, the current induced mechanisms and compositional inhomogeneity. Recently, a study made by Huixin Xiu et al. concludes that the leakage current induced optical degradation may play a key role for the degradation of DUV-LEDs [2]. They set an experiment to test the degradation. The stress test was run on LEDs with a temperature of 25 degrees Celsius and a current of 20 mA. The research team examined the spectrum of the test LEDs and used microscopes to observe the location of degradation in the LEDs. The effect of degradation is clearly shown in Fig. 1 [2].

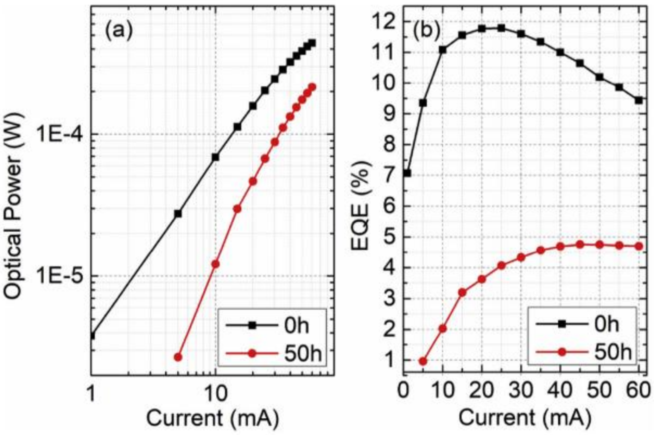

Fig. 1 Optical power (a) and (b) EQE dependence on the forward current for LED B before and after 50-h aging [2]

After 50 hours of lighting, both the optical power and the External Quantum Efficiency (EQE) are significantly affected by degradation. Especially the EQE, it has reduced more than 50%, which makes the efficiency of DUV-LEDs more unsatisfying. It is also suggested in Fig 1a that the optical power degradation is worse at low current conditions, indicating the existence of SRH recombination. The decrease of EQE is attributed to the SRH recombination and the current leakage.

EDX mappings is also applied to analyze the degraded LED and the result is compared with a normal LED. The interface between p-GaN and p-contact can be rougher, suggesting a possibility of the creation of a leakage pathway.

2.2. The generation of defects induced degradation

Defects are unavoidable in the production of the materials to build DUV-LEDs. It has already been confirmed that defects can lead to decline in efficiency. But this opinion is not comprehensive, the effect of defects on degradation is also remarkable. Defects can work as nonradiative recombination centers and cause current crowding and heating [3]. These centers can also accelerate the degradation of LEDs, reducing efficiency while aging, leading to the decrease of optical power after stressing [4].

The analysis of Ga vacancy proves that stressing can leads to the generation of new defects. Ying-Zhe Wang discovers that after stressing the ultraviolet LED made by AlGaN, the light emitted from the LED turns to yellow instead of blue or purple [5]. This phenomenon is suggested by the spectrum, as Fig. 2 shows.

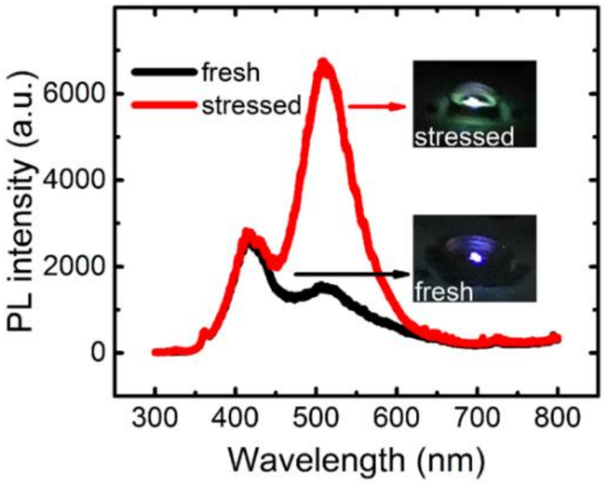

Fig. 2 PL spectra of UV-C LED before and after electrical stress (take 900 ks as an example) at room temperature (295 K) [5]

The insets are the image of the fresh and stressed UV-C LEDs during measurement, respectively. It is noticeable that the PL intensity of light with a wavelength of 515 nm increased dramatically making the light more yellow.

Ying-Zhe Wang mentioned that this change in the LED is because the transition with Ga vacancy [5]. The three main causes of Ga vacancy have been confirmed by previous studies: The division of Ga, Si and Mg atoms from the location of Ga in AlGaN. It is important to determine which kind of atom takes the major part of the division in order to find a solution to mitigate degradation. The energy barrier of the division of Mg is 25.9% and 26.1% lower than Ga and Si, respectively. Additionally, the formation energy of Mg is 28.4% and 21% lower than Ga and Si, respectively. Therefore, Mg atoms take the major part of the Ga vacancy. The existence of Mg atoms should be paid enough attention to expand the lifespan of DUV-LEDs.

3. The Analysis of Factors of Degradation

3.1. Current research analysis

There are multiple experiments about the effect of current on degradation of DUV-LEDs. All of them reached the conclusion that a higher current density will boost the degradation of DUV-LEDs. These experiments often set the current range from 30 mA to several hundred mA. After hundreds of hours of lighting, the LEDs are compared.

Jan Ruschel designed experiments to test the degradation [6]. He set the currents of 50 mA, 100 mA, 200 mA, 300 mA and the current densities were 33.5 A/cm^2, 67.0 A/cm^2, 134 A/cm^2, 201 A/cm^2, respectively. Then he put these 4 sets of LEDs to a continuous work. There were 15LEDs in each set. For the LEDs which worked with a current of 50 mA, it was tested for 4300 hours and the rest of the LEDs were tested 1000 hours each. These four sets of LEDs were kept under a same, constant temperature to avoid the acceleration of degradation brought by a higher temperature. Optical power over time of LEDs run at different current densities is shown in Fig. 3.

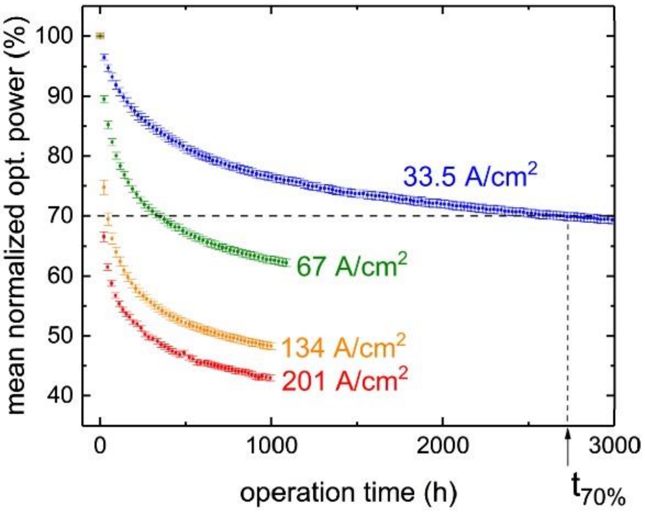

Fig. 3 Optical power over time of LEDs run at different current densities [6]

The values are normalized to the initial value and averaged over 15 LEDs. For all currents, the junction temperature was kept at (90±5) °C. It shows the result of the experiment and it suggests that under higher current, the degradation has a higher rate. It could also be discovered that the rate of degradation is faster at the beginning, then the rate will decrease while the working hours accumulates. Jan Ruschel also points out an interesting phenomenon that degradation rate is almost independent with the current density at long operation times [6].

Similar experiments to explore degradation under pulsed current had been applied either. Z. Gong designed an experiment to test gradual degradation of DUV-LEDs under pulsed working currents and different ambient temperatures [7]. The pulse was set with 1 microsecond and 5% duty cycle. This designation can reduce the heat generated by the LEDs themselves, reducing the error brought by the difference of temperature. These LEDs were kept working for 20 hours and the figure was made based on the data from the beginning 1 hour. Output power vs stress time under various ambient temperature a and pulse current b stress conditions is shown in Fig. 4.

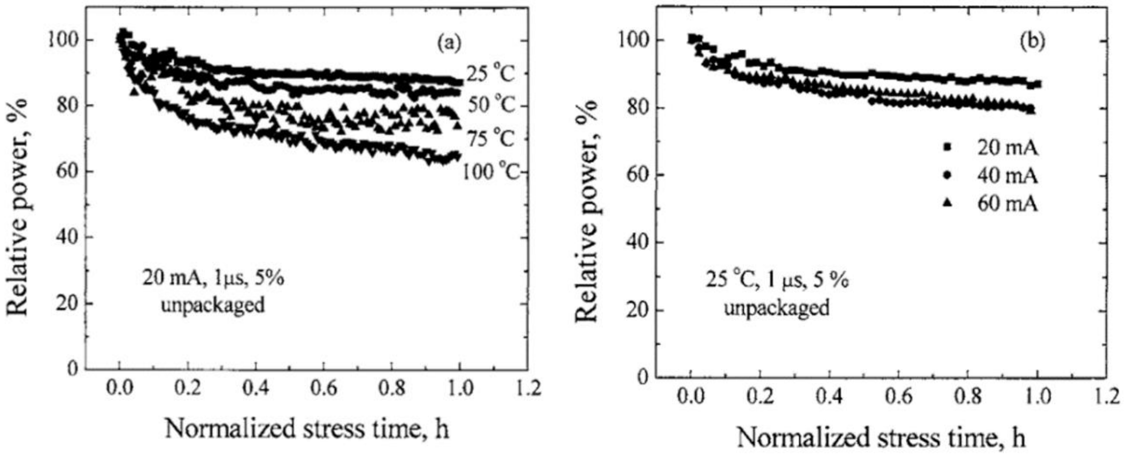

Fig. 4 Output power vs stress time under various ambient temperature a and pulse current b stress conditions [7]

Fig. 4 (b) shows the trend that a higher current will lead to a higher rate of degradation. However, the output power seems counterintuitive with the current of 40 mA and 60 mA since the power of 60 mA is supposed to be lower than that of 40 mA. This phenomenon may be explained by the different original power. The original output power under a current of 60 mA is larger than the output power under a current of 40 mA. With a greater rate of degradation, the output power under 60 mA is reduced to almost equal to the output power of 40 mA after a continuous work of an hour. Fig. 4 (a) represents the result under same current with different surrounding temperatures. It suggests that heat may play a bigger role in the degradation of LEDs. The trend of the degradation rate is similar to the trend under different currents.

In summary, the results of the experiments exploring the degradation rates of different currents suggests that a higher current density will cause the LEDs to age faster. From the figures made by the data also points out a regular pattern of the degradation. LEDs tends to age faster at the beginning, and the rate of degradation will slow down. However, the mechanism behind this phenomenon has not been fully explored. It seems that researchers are more interested in the degradation brought by temperature.

3.2. Heat and defects

When manufacturing the material to build a LED, defects are unavoidable to be grown during the process because of the characteristics of the material and the impurity of the material. The material which has been widely used to build a DUV-LED is AlGaN. GaN:Mg is often used as the contact layer. The existence can provide unexpected Mg doping and affects the performance of a LED, for example. Defects can cause the temperature of the LED in increase, and the higher temperature, in some degrees, will lead to the generation of more defects. Thus, a higher temperature will cause the LED to age faster and defects are related to the rise of the temperature.

It is suggested that the mechanism which leads to the aging of devices and redshift could be probably explained as the process below: The relatively large current that flows through the domain-like area causes local heating in the material, rising the temperature. The higher temperature enhances the migration of atoms, inflicting to the decrease of local potential. At the meanwhile, the decreased local potential allows the current to increase, so the current flows through the domain-like area is increased, forming feedback. It is also noted that such process is often accompanied by the creation of defects, causing the acceleration of degradation, eventually makes the LED to fail [8]. Chitnis, A. et al. design an experiment to explore the effect of heat management on the performance of DUV-LEDs. The result of the experiment is shown in Fig. 5 [9].

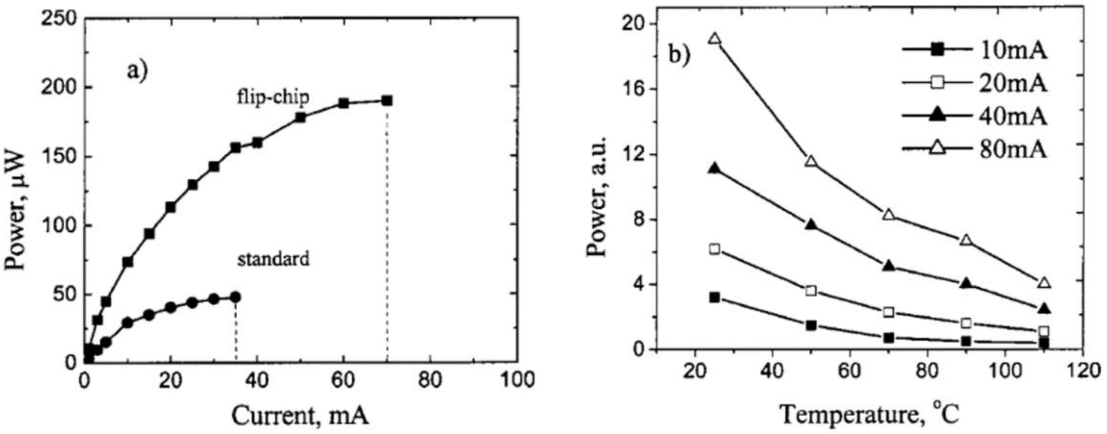

Fig. 5 (a) DC output power of standard and flip-chip mounted UV LEDs vs pump current. (b) Output power vs pulsed pump current for flip-chip mounted UV LED for different temperatures [9]

From the curves in Fig. 5(b), the output power of LEDs is decreased with the effect of both current and heat. However, the difference of degradation brought by current is limited since the differences of the current are not great enough, the effect of heat plays the major role in the degradation. With higher operation temperature, the output power decreases more severe. It is also worthy to mention that the higher the working temperature, the severer the degradation is. Fig. 5(a) suggests the similar condition discussed in the previous paragraph. Two types of chips are explored. The flip chip has a better heat dissipation condition so the working temperature of the flip chip is lower than the standard chip. It is clearly shown that the LED with a cooler temperature can have a better performance. It is also suggested that self-heat is the reason accounts for the premature saturation in LEDs driven by direct current [9].

Matteo Meneghini et al. states that the increase of defects can cause the gradual reduction of radiative efficiency and benefits degradation [10]. It is because the stress, may come from current or heat, can increase the concentration of defects. The vast decrease of optical power under lower current condition suggests that defects can effectively make the degradation more severe. All this conclusion is suggested by Fig. 6 [10].

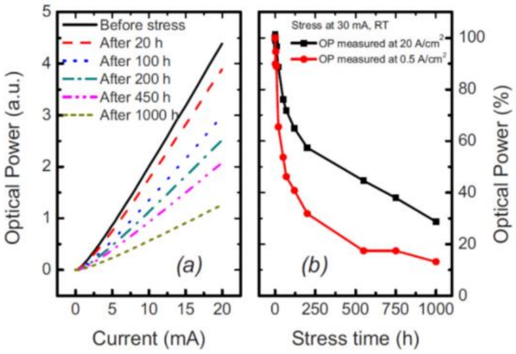

Fig. 6 (a) L-I characteristics measured on one of the analyzed devices submitted to stress at 33 A/cm^2, RT. (b) OP degradation measured at different current levels during stress on the same [10]

In summary, heat and defects can greatly influence the reliability and the performance of DUV-LEDs. The lifespan could be strongly affected by heat, especially the heat generated by the material. Also, defects could be created under stress, including high temperature and high current density. Therefore, heat dissipation devices should be applied to the LEDs to extend its lifespan and improve its performance. With higher performance, the lower current would be needed to put a LED to work and satisfy the requirement.

3.3. I-V Characteristics After Aging

It is clearly demonstrated that the source of stress of a LED can be current and heat. These two factors and defects can accelerate the degradation of DUV-LEDs, causing the efficiency of the LEDs to reduce significantly. The impact of degradation on LEDs can be catastrophic and comprehensive. Also, the I-V characteristics can suffer from degradation for multiple aspects. The reverse current is increased with the same voltage applied compared to the LED before aging, and the voltage required to reach the same output power and current before aging has increased when the working voltage is higher than the threshold. When the applied voltage is lower than threshold, the current will increase.

Meneghini, M. et al. explore the I-V characteristics of stressed LEDs and find the indication of degradation [11]. They set an experiment and test the I-V characteristics of one LED during the stress and Fig. 7 is made based on the data. The figure is made in semi-logarithmic scale.

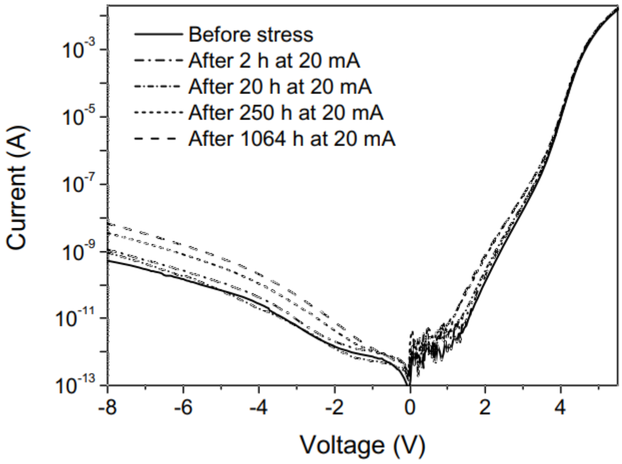

Fig.7 I-V curves measured before and during stress on one of the LEDs emitting at 295 nm [11]

The figure indicates the increase of reverse current during stressing, showing the change of the p-n junction inside the LED. The reverse current gradually increases with the extension of stressing time. At the meanwhile, the current with an applied forward voltage, which is lower than the threshold voltage, also increases. Similarly, the output power decreases, suggesting that optical degradation is related to electrical degradation [11]. Su, M. et al. reach the similar result. The difference between these two experiments is, Meneghini, M. et al. test the LED applying the same current but various time, while Su, M. et al. test the LED for 24 hours with different currents applied.

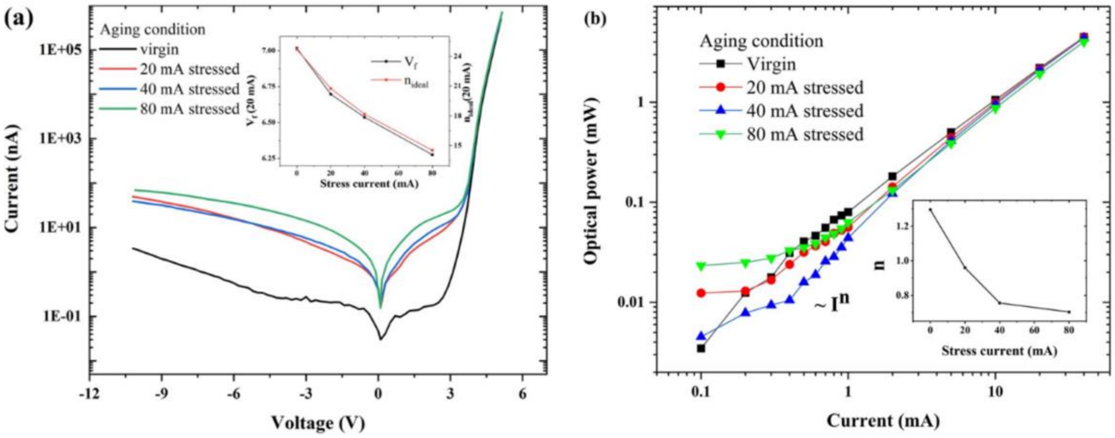

Fig. 8 (a) I–V characteristics of samples stressed at different stress currents. Inset: forward voltage (Vf) and ideality factor variation (n_ (idea;)) measured at 20 mA of 280 nm UV-LEDs under different stress currents. (b) The L–I characteristics of samples measured at different stress currents. Inset: the exponential relationship between current and optical power caused by the different stress currents [12]

From Fig. 8(a), the curves indicates that both the reverse current and the current with voltages lower than threshold voltage increases. The worse the degradation is, the more the current increases. Fig. 7 and Fig. 8 proves that the current will increase when the forward voltage is lower than threshold or the voltage is reversed after aging.

Fig. 9 is more comprehensive [13]. From the figure, when the voltage becomes higher than the threshold, the current appears to be lower than the characteristic before aging. This situation obeys the conclusions of the effects of degradation.

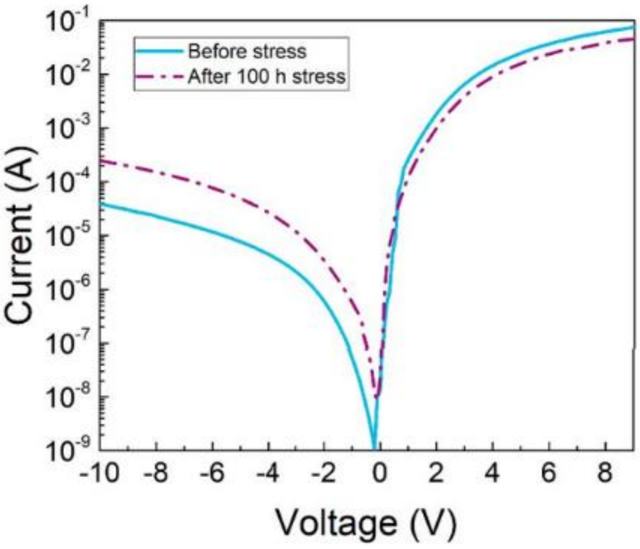

Fig. 9 Typical I–V curves of (In)AlGaN-based DUV LED measured before and after stress treatment [13]

In summary, when the voltage is lower than the threshold or it is reversed, the current will increase; when the voltage is higher than the threshold, the current will reduce due to degradation.

4. Optimization With New Technology and Expectations in The Future

The degradation effect of DUV-LEDs has been fully explored by researchers and important conclusions have been made. Several key factors that can greatly affect the lifespan and the performance of DUV-LEDs, for instance, current and heat, have been confirmed. The mechanisms behind the aging phenomenon have also been explored. After hundreds of hours of aging and stressing, the reduce of efficiency is predictable. However, these problems do not seem to bother most of the scientists because they still believe that DUV-LEDs have a satisfying lifespan. Indeed, LEDs have a much longer lifetime than other sources of light that we currently have. Yet, the reduction of efficiency is so severe that in some extreme conditions, the efficiency could decrease to only half of the original state. Researchers and developers of DUV-LEDs need to pay more attention to this problem, considering the original external quantum efficiency is only 20.3% which is not so satisfying [14].

There is also some good news to learn. With the development of technology, special materials have been discovered recently to be useful to enhance the performance of DUV-LEDs. Hongliang Chang et al. apply graphene to the growth of AlGaN and successfully decreases the hetero-mismatches and dislocations inside the material [15]. With the help of graphene, there would be lower concentration of defects. The performance of DUV-LEDs has been improved either. The output power reaches 2.1 times larger than the AlGaN grown on bare sapphire. This interesting usage of graphene brings incredibly enhancement to DUV-LEDs and this kind of research should be encouraged. The invention of such technology is surprising, but the exploration of this new technology is not comprehensive enough. The cost of the application still remains unknown and the stability of the technology has not been studied. Further analysis of this technology and its LEDs must be conducted. New experiments should be designed to study how would the LEDs with graphene degrade after stressing. How bad the degradation would affect the LEDs should also be carefully tested. It is personally believed that graphene will help researchers to improve the performance and reduce the effect of aging. Also, more new types of material should be tested in order to find out new characteristics of both the material and LEDs.

Heat, among those factors that can affect the aging of LEDs, undoubtfully plays a big role in the degradation of DUV-LEDs. Designing new heat dissipation method or devices is another direction to improve the lifespan of LEDs. The flip-chip installation of LEDs in Fig. 5(a) is a good example of this suggestion. With a better heat dissipation condition, the degradation rate of LEDs can be improved and the output power can be increased drastically.

5. Conclusion

This paper reviewed the basic mechanisms behind degradation, summarize the three main factors that can facilitate the degradation and the effect of degradation on the DUV-LEDs. It is clear that current, heat and defects can cause the degradation and lead to the reduction of performance, shortening the lifespan. A higher current, a higher temperature and a higher concentration of defects will increase the rate of degradation. What is more, a higher temperature, in some circumstances, can cause the generation of defects, thus, making the local heat more intense and may lead to more creation of defects. Fortunately, some new materials, such as graphene, have been applied to the manufactural process to produce better products with less defects. It is believed that these new applications and new technologies will improve the performance, reliability and lifespan of DUV-LEDs.

However, methods provided by former articles have not been confirmed useful in this passage yet. The extent to which the application of graphene can improve the lifespan of DUV-LEDs is also uncertain. There should be carefully designed experiments to test the newly developed DUV-LEDs to explore its reliability and its performance. At the meanwhile, the external quantum efficiency is also a great problem with DUV-LEDs and the problem hinders the commercialization of DUV-LEDs. It is undoubtful that there will be new technologies to improve the performance. It is suggested that the reliability should be tested and included in the experiments in the future.

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