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Research Article

The Effect of Package Structure on the Light Extraction Efficiency of Near-Ultraviolet LED

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The near-ultraviolet high-power LED, with five package structures, is designed and fabricated. The efficiency of electric conversion to light (EECL) of various package structures is measured, and the EECL is used to characterize the light extraction efficiency (LEE) of the package structure. By analyzing the Fresnel loss (FNL) and total inner reflection loss (TIRL) of light at different interfaces, the experimental results are explained qualitatively. When approximate spherical lens is used, filling silica gel between chip and lens can improve the LEE. The EECL of the device can reach 66.84%, which is higher than that of bare chip by 55.10%. In planar packaging, the EECL of the device is lower than that of the bare chip, whether or not it is filled with silica gel. After filling with silica gel, a new TIRL is produced at the final interface of the device, and the EECL of the device is even lower, which is only 37.14%. The experimental results show that when the LED chip adopts graphic substrate and surface microstructure to improve the LEE, the traditional coating of silica gel (or epoxy) and other materials on the chip surface may not improve the LEE of the device. If the introduction of the silica gel layer leads to a new total inner reflection interface, it will result in a significant decrease in LEE of the device. When a layer, such as silica gel, does not result in a new total reflection interface, the FNL and TIRL of the chip surface can be effectively reduced, and the LEE of the LED device can be improved.

1. Introduction

Ultraviolet light emitting diode (UV LED) has the advantages of small size, long lifetime, and high efficiency. It is used in fluorescence detection, high-resolution microscope, UV exposure, UV curing, medical application, biological analysis, and other fields have a wide range of application prospects [1–3]. According to the peak wavelength of the spectrum, ultraviolet LED is divided into three categories: UVA ($315\,\text{nm} < \lambda \leq 420\,\text{nm}$), UVB ($280\,\text{nm} < \lambda \leq 315\,\text{nm}$), and UVC ($200\,\text{nm} < \lambda \leq 280\,\text{nm}$). UVA-LED has been mature in epitaxial growth and chip fabrication, and the current research focuses on device package structure and application product development. UVC-LED has great application prospects in sterilization and water purification. However, the internal quantum efficiency of UVC-LED chips is still very low. Designing new epitaxial structures and improving the growth technology of materials is the focus of many national research institutions [4].

The wavelength of UVA-LED is similar to that of blue LED. At low power, the UVA-LED package structure is very close to the blue LED, except that epoxy resin and ordinary silica gel are replaced by modified silica gel with better anti-UV performance [5]. The surface of the early LED chip is a smooth plane. When the refractive index of the chip material is different from that of the air, there is a serious total reflection phenomenon on the chip surface. Corresponding to the interface between the GaN material and the air, the half-space angle of the exit light cone is only about 24°. Using silica gel as the transition layer can greatly improve the light extraction efficiency (LEE) from the chip interior. In recent years, with the new technologies [6–10], the graphical substrate and surface microstructure destroy the full reflection condition of the chip surface; the total reflection effect at the interface between chip and air has been greatly reduced. The effect of polymer packaging materials such as silica gel and epoxy resin on improving LEE was also weakened. At the same time, when the final light-out interface is flat, like

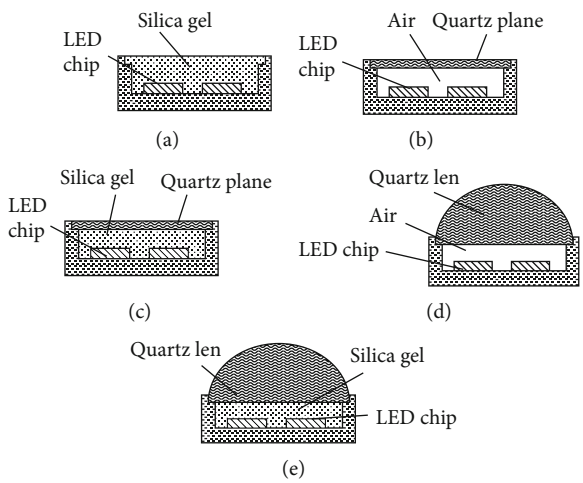

Figure 1: Diagram of different package structures.

the "chip-air-quartz plane" package structure in the article, the use of polymer materials will produce a serious inner total reflection loss (TIRL) in the final interface. This results in a decrease of the light extraction efficiency. This is also the main difference between this paper and traditional packaging theory.

In the early stage of LED package, all-inorganic metal-ceramic package structure was adopted. In order to reduce the cost and improve the LEE, epoxy resin with refractive index between air and chip material was introduced. After the emergence of blue-light LED and near-ultraviolet LED with shorter wavelengths, in order to overcome the yellowing phenomenon of epoxy materials, silica gel with better antiultraviolet properties was used to replace epoxy materials. With the extensive application of near-ultraviolet LED in printing industry, the optical power density of LED becomes higher and higher. In the devices and modules of near-ultraviolet LED with high power density, the yellow change of silica gel becomes the serious problem of LED application once again. In fact, if the use of silica gel in UVA-LED packaging only results in the degradation of performance and the reduction of its lifetime, the use of silica gel filling layer will have disastrous consequences when UVC-LED is widely used. In this paper, the encapsulation structure of the chip-air-quartz sphere is studied. There is no organic material in the light path, which can avoid the deterioration of the performance of organic material (silica gel) under strong ultraviolet irradiation. Moreover, the technology of graphic substrate and surface microstructure is adopted; the near-UV LED chip can obtain high LEE without using silica gel. This all-inorganic metal-Quartz lens package may be the best choice for high-power UVA-LED and UVC-LED in the face of new application requirements.

2. Package Structure and Experimental Results

2.1. Package Structure Design. In order to compare the LEE of near-ultraviolet LED with different package structures, five different package structures were designed, as shown in Figure 1, corresponding to package structure 1 (chip+silica gel, Figure 1(a)) and package structure 2 (chip+air+quartz plane, Figure 1(b)), package structure 3 (chip+silica gel+quartz plane, Figure 1(c)), package structure 4 (chip+air+quartz lens, Figure 1(d)), and package structure 5 (chip+silica gel+quartz lens, Figure 1(e)). In these structures, the outer surface of the quartz lens is approximately spherical.

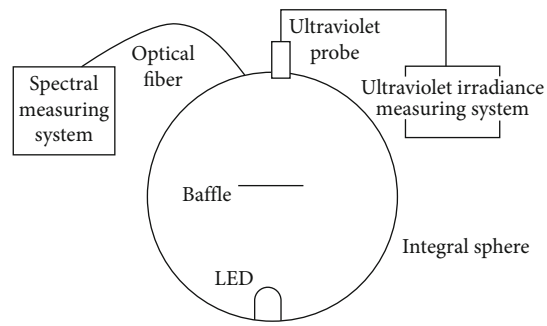

Figure 2: Test principle of LED light color electrical parameter comprehensive tester.

The sample is made of ceramic substrate 7070 high-power LED special mount and four GaN-based near-ultraviolet LED chips. The peak wavelength of the chip is located in the 400.0-402.5 nm range, the chip size is 1140 square, and the chip thickness is 195 μm ± 25 μm. The anti-UV transparent silica gel, KER2936, with a refractive index of 1.54 was used. In the experiment, the quartz plate thickness used was 0.6 mm, the quartz lens is a hemispheric structure with a radius of 5.8 mm, and the upper surface of the LED chip is 0.4 mm from the lower surface of the lens (this distance is the thickness of the filled silicone or air layer).

When the sample is made, the chip is first glued to the mount with silver paste and cured in the 180°C thermostatic oven for 60 minutes, making the LED chip and bracket firmly bonded. Then, the electrode between chips is connected by 30 μm diameter gold wire and ultrasonic gold wire ball welding process. Finally, cover the surface of the chip with silica gel (packages 1, 3, 5) and cover the quartz glass flat (packages 2, 3) or quartz lens (packages 4, 5). According to the designed connection mode, two series and two parallel connections are formed, and the input current is 500 mA. The typical power of the sample is 3.2 W.

2.2. Measurement Principles and Results. The photoelectric parameters of the devices are measured by SSP 3112 LED photochromic parameter tester. The measuring instrument is composed of driving power supply, integral sphere with 0.5 m diameter, ultraviolet irradiance measuring system, spectral measuring system, etc. The structure is shown in Figure 2. The interior of the integrating sphere is coated with diffuse reflection coating and has high reflectivity in the wavelength range of 350 nm-780 nm. The system is calibrated by the standard light source, in the 400 nm band; the accurate UV radiation emission flux can be obtained. During the measurement, the light emitted by the LED light source is diffuse reflected through the surface of the integrating sphere for several times, and part of the light is incident on the optical fiber behind the baffle and the ultraviolet probe, which is used to measure the wavelength distribution and the ultraviolet radiance, respectively. The main function of

Table 1: Radiation flux and electrooptical conversion efficiency of different package structures.

Package structures	Electric power (mW)	Radiation flux (mW)	EECL (%)	Peak wavelength (nm)
Bare chip	3224	1776	55.09	402.2
Package 1	3304	1183	35.80	401.8
Package 2	3294	1617	49.09	402.2
Package 3	3293	1223	37.14	401.5
Package 4	3252	1705	52.44	401.9
Package 5	3303	2206	66.83	401.4

the baffle is to prevent the direct light; the influence of the spatial distribution can be avoided.

In the experiment, the efficiency of electric conversion to light (EECL) is used to characterize the LEE of the package structure, compared to wall plug efficiency; EECL does not include the loss of the drive power supply. For the same batch of near-UV LED chips are used, the internal quantum efficiency of the chips is basically the same. That is to say, the difference of ultraviolet radiation flux is caused by the package structure, and it is reasonable to use the difference of ultraviolet radiation flux to represent LEE of different package structures. In order to eliminate the influence of the discreteness of the chip parameters, five samples were fabricated in each package structure, and all the measured results were taken as the arithmetic average of five samples. For comparison, five samples of bare chips were made, with no silica gel or quartz glass on the light exit path. The test results are shown in Table 1; because of the difference in the forward input voltage of different chips, the EECL in the meter is calculated from the measured ultraviolet radiation flux/input electric power, and the test using pulse driven, the width of the pulse is only 50 ms; the chip's thermal effect can be ignored.

There is a difference of less than 3% in the electrical power and 1 nm in the wavelength of different package structures, mainly because of the discrete type of the performance of the chip itself. Because the difference is so small, the difference of electrical power and wavelength will not affect the experimental results of the article.

The experimental data in Table 1 show that (1) the EECL of package 5 is higher than that of the bare chip, and other package structures are lower than it. (2) For the two kinds of planar structures with silica gel layer, whether it is package 1 or package 3, their EECL is much lower than that of the bare chip. It is only about 65% of the bare chip. (3) The EECL of the package 2 is nearly 12% higher than that of the package 3. In other words, in the case where the final light surface is planar, the EECL decreased greatly after the silica gel layer was inserted. (4) The EECL of the package 4 is about 18% higher than that of the package 2, that is to say, in the case of the final light surface approaching the spherical, the silica gel layer can improve the EECL of the device.

Under the same conditions, the EECL (or internal quantum efficiency) of the chip is basically the same, and the difference of the EECL of the whole device is caused by the different LEE of the package structure. In the traditional design of LED package structure, it has always been thought that LEE can be improved by a layer with refractive index between air and chip material. However, the experimental results in Table 1 are obviously different from the traditional package structure design theory.

3. Effect of Interface Reflectance on Light Output Efficiency

3.1. Main Types of Interface Reflection Loss. LEE of package structure needs to be considered, that is the biggest difference between LED and integrated circuit package structure design. This efficiency is intuitively understood as the ratio of the number of photons (or flux) emitted outside the device to the number of photons (or flux) produced in the LED chip. Besides the absorption loss includes chip material, packaging adhesive, mount surface, die bonding adhesive, and lens. The reflection loss formed by different materials is the main factor that determines LEE. From the point of view of physical mechanism, the reflection loss at the interface can be divided into FNL and TIRL.

When the refractive index of the two sides of the interface is different, some of the light incident at the interface will be reflected back, resulting in the loss of light energy, which is named as the FNL. The refractive index and the difference of refractive index of the optical medium on both sides of the interface are the key factors to determine the FNL. In addition, the FNL is also related to the incident angle and polarization state of the light, so the quantitative analysis is very complicated. In general, the Fresnel reflection coefficient of the two interfaces at the time of vertical incidence is as follows:

$$\Gamma = \left(\frac{n_2 - n_1}{n_2 + n_1}\right)^2. \quad (1)$$

When light is incident through the interface formed by two media, the relationship between the angle of incidence and the refraction follows Snell's law:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2. \quad (2)$$

When light is emitted from a medium with a large refractive index to a medium with a small refractive index, if the incident angle of the light is greater than a critical value θ_c, the total reflection will occur at the interface. This critical value θ_c is called the full reflection angle, which can be obtained from the following formula:

$$\theta_c = \arcsin\left(\frac{n_2}{n_1}\right). \quad (3)$$

In the LED package structure, the TIRL is much higher than the FNL, which is the primary factor to be considered in the structure design of the LED package.

3.2. Comparison of Interfacial Reflectance Loss of Package Structures. When ITO conductive film is used on the surface

Table 2: Comparison of two losses of different package structure interfaces.

Package structure	EECL (%)	The Fresnel loss			Total inner reflection loss		
		Interface 1	Interface 2	Interface 3	Interface 1	Interface 2	Interface 3
Bare chip	55.09	L			L		
Package 1	35.80	AL	H		AL	H	
Package 2	49.09	L	H	H	L	N	N
Package 3	37.14	AL	AL	H	AL	AL	H
Package 4	52.44	L	H	AL	L	N	AL
Package 5	66.83	AL	AL	AL	AL	AL	AL

of the chip, the materials related to light extraction and their refractive index are ITO ($n = 2.0$), air ($n = 1.0$), silica gel ($n = 1.51$), and quartz glass ($n = 1.46$), respectively. For the convenience of analysis, starting from the chip surface, the interface consisting of two kinds of media is defined as interface 1, interface 2, and interface 3 along the path of light extraction.

There are two situations for interface 1; the materials on both sides of the interface are (1) ITO and air (corresponding bare chip, Figure 1(b), Figure 1(d)) and (2) ITO and silica gel (corresponding to Figure 1(a), Figure 1(c), Figure 1(e)). Both cases are incident from high refractive index medium to low refractive index medium, and there will be light loss caused by total reflection on the surface. After the surface microstructure is adopted in the chip, the total reflection effect is well suppressed. In contrast, in the first case, the TIRL and FNL at the interface are higher than those in the second case because of the higher refractive index difference between the two media.

There are three situations for interface 1; the materials on both sides of the interface are (1) silica gel and air (Figure 1(a)), (2) silica gel and quartz (Figure 1(c), Figure 1(e)), and (3) air and quartz (Figure 1(b), Figure 1(d)), all of which are smooth planes. In the first case, the refractive index difference between the two media is large; the FNL is relatively high. The light is incident from high refractive index medium to low refractive index medium; there is a serious total reflection, and the corresponding total reflection angle is 41.5°. In the second case, the refraction of the two media is very close, and the corresponding TIRL and Fresnel are very small. In the third case, although the refractive index difference between the two media is relatively large, there is a higher FNL, but because the is incident from low refractive index medium to high refractive index medium, there is no TIRL.

At interface 3, the refractive index of the media on both sides of several package structures is the same, because of the different shapes of the interface, one is plane and the other is spherical, resulting in a great difference value of FNL and TIRL in the interface. In the case of spherical surfaces (corresponding to Figure 1(d), Figure 1(e)), the incidence angle of most light incident to the interface is very small, close to the vertical incidence; the proportion of large angle incident light is very small, and the TIRL can be negligible; FNL is also small. In the two cases where the interface 3 is a plane (corresponding to Figure 1(b), Figure 1(c)), there is a large proportion of large angle incident light, and the FNL is high. In the structure of Figure 1(b), the refractive index of the medium on both sides of the quartz plane is the same, and there is no case where the incident angle is greater than the total reflection angle, that is to say, there is no TIRL in the interface 3 of Figure 1(b). In the structure of Figure 1(c), the light incident to interface 3 can be approximately regarded as Lambert luminous body, and there are many rays whose incident angle is greater than the total reflection angle; there is a serious TIRL in interface 3.

3.3. Qualitative Analysis of Experimental Results. In order to describe the relationship between the optical loss at the interface and LEE of the package structure, the loss is divided into three levels: high (H), low (L), and a little (AL). Here, "high," "low," and "a little" are mainly qualitative comparisons between the different packaging structures, not a quantitative comparison. Even at the same level, not only does the Fresnel loss (FNL) and total inner reflection loss (TIRL) numerically vary greatly, but the same loss mechanism varies greatly at different interfaces. The FNL and TIRL of different interfaces in various package structures are compared as shown in Table 2, and the EECL of various package structures is also listed in Table 2.

It can be seen from Table 2 that whether there is a high TIRL, the package structure is the most important factor to determine LEE. In the package structures of package 1 and package 3, through the introduction of silica gel, the TIRL and FNL on the chip surface are reduced, but a high TIRL is produced in the final light extraction interface, which makes LEE of the two package structures the lowest. When quartz lens is used, the final interface of light extraction is spherical. After the light emitted through various media, the light emitted by the chip is incident to the interface at a small angle, and the TIRL and FNL are very small. At this time, filling silica gel between the chip and the quartz lens can reduce the FNL and TIRL at the chip surface, and LEE of the package structure can improve. Package 5 is the only package structure in which LEE is higher than that of bare chip.

4. Conclusion

After using graphical substrate and surface microstructure technology, LEE of bare chip has been greatly improved. In this case, when the planar package structure is adopted, the silica gel is filled between the chip and the quartz plane, and a new TIRL is produced in the light interface of the

package structure, which leads to LEE of the packaged device is lower than that of the bare crystal. This is different from the traditional idea of package structure design. In the spherical package structure, filling silica gel between the chip and the spherical lens can reduce the FNL and TIRL on the chip surface, while no new TIRL will be produced in the final output interface. LEE of package structure can be effectively improved. The molded silica gel spherical package structure can reduce an interface, reduce the corresponding FNL and TIRL, and further improve LEE of the package. This structure can be used in the low-power near-ultraviolet LED. In long-term use, the silica gel turns yellow, affecting the transmission efficiency of light and reducing performance; the degradation of silica gel is an inevitable problem, and it is difficult to be applied.

Another thing worth noting is the package 4, which has no organic matter in the exit path of light, and LEE of this structure is also relatively high, which is close to the LEE of the bare crystal. As long as the spherical shell concave lens is used, the Fresnel reflection on the lower surface of the quartz lens will be greatly reduced, and LEE will be further improved. With the optimization of graphical substrate and surface microstructure of LED chip, LEE of bare crystal will be further improved. At this time, this all-inorganic package structure has the advantages of UVC device packaging.

The factors affecting the light efficiency of near-UV LEDs are qualitatively analyzed; if numerical simulation methods can be used to quantitative analysis, the FNL and TIRL of each interface will undoubtedly be able to provide more powerful guidance on the optimization of device structure. In addition, far-field and near-field optics are important for device applications. Due to the limitations of the conditions, this article does not cover the above two aspects; this is our next step to study; we are also looking forward to working with interested researchers on the abovementioned issues.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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