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Original research article

Influence on temperature distribution of COB deep UV LED due to different packaging density and substrate type

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\textbf{ABSTRACT}

The thermal performance of a deep UV LED package in three different chip on board (COB) substrates was studied by finite element simulation. The relationship between the temperature of each component in different COB substrates and the packaging density of the deep UV LED was analyzed. Having the same size of a 1313 COB substrate, this study indicates that the aluminum substrate can adapt to a 0.38 W/mm\textsuperscript{2} packaging density at a maximum owing to the existence of an insulation layer, which has a low thermal conductivity. However, an alumina ceramic substrate can be adapted to a 0.94 W/mm\textsuperscript{2} packaging density. Aluminum nitride ceramic can meet the demand for a higher packaging density; however, the cost is a key factor which cannot be ignored for large-scale applications. The results of this study provide detailed suggestions for researchers and industrial use for the selection of COB substrates packaged with deep UV LED according to different packaging densities, which have a higher practical application value.

\section{Introduction}

This year, the novel coronavirus (COVID-19) has broken out globally, posing a serious threat to people and property. The novel coronavirus infection pneumonia diagnosis and treatment scheme (Trial Version IV) released by the National Health Commission of China clearly indicated that the novel coronavirus is sensitive to UV light and heat \cite{1}. Depending on the wavelength coverage, UV light can be divided into shallow and deep UV light, where deep UV light (UVC) has a significant bactericidal effect. The sterilization mechanism consists of the genetic material, such as DNA and RNA, of microbes being absorbed by large amounts of deep UV light, eventually being destroyed by deep UV energy and losing the ability to copy and reproduce; furthermore, this does not produce a peculiar smell which does occur with the physical sterilization method. Signify has announced that in a joint study with Boston University, their UVC product can effectively inactivate the novel coronavirus COVID-19; a 5 mJ/cm\textsuperscript{2} radiation dose (radiation time of 6 s) successfully inactivated 99 \% of the novel coronavirus \cite{2,3}.

Currently, the UVC light sources mainly include mercury lamps and UVC LEDs. Although mercury lamps have been widely used, they have several disadvantages such as a short life, low efficiency, slow reaction, as well as the fatal disadvantage of toxic mercury. On January 19, 2013, more than 120 countries have signed the Minamata Convention, which aims to gradually replace traditional UV light sources (mercury lamps) and reduce the use (or eradicate) of large quantities of mercury-containing UV products by 2020 \cite{4}. UVC LEDs are considered as ideal substitutes for mercury lamps owing to their advantages of energy saving, environmental protection,
quick response, long lifetime, less heterochromatic light and noise, as well as DC power supply [4]. However, owing to the difficulties in the growth and manufacturing process of epitaxial materials, the external quantum efficiency of UVC chips remains significantly low (<10 %), and commercial UVC LEDs are generally lower than 3% [5], while that of commercial blue LEDs or UVA LEDs is approximately 50 %. Therefore, UVC LED is facing with a critical thermal management problem, which if not controlled, will reduce the radiation energy, or even worse, directly affect the lifetime of the device. Moreover, to ensure that the UVC LED meets the requirements in the field of disinfection and sterilization applications, it is difficult for a single chip to satisfy the requirements of the required UV intensity, which must be achieved by multi-chip integrated packaging.

Chip on board (COB) is a mature technology that enables the direct packaging of multiple chips on a substrate [6], and can meet the disinfection and sterilization requirements of UVC LEDs. However, with the increase in chip packaging density, packaging thermal management has also become a problem that cannot be ignored. In particular, when the design optimization of the heat dissipation of lamps is close to saturation, optimizing the packaging thermal management is a key method that can be used to enhance heat dissipation.

Several studies regarding LED packaging thermal management have been conducted. Bang [7] optimized the packaging structure of LEDs by adding a ceramic segmentation layer, and lowered the junction temperature of the LED from 114 °C to 109 °C. Kim et al. [8] proposed a new silicon-based LED package structure that improves the reliability and lifetime of the device by optimizing the heat dissipation. Christensen et al. reported that the thermal performance of LEDs depends on the spacing between adjacent chips [9,10]. In addition, researchers have found that the heat dissipation of high-power LEDs is related to the welding process [9,11]. Kang et al. proposed a liquid package LED structure that not only improved the light output efficiency, but also reduced the thermal resistance by approximately 30 % [12]. Lan Hai et al. studied the package thermal resistance of different COB substrates, and optimized the COB LED package to enhance heat dissipation by using materials with high thermal conductivity or reducing the thickness of the bonding layer [13]. However, only a few studies on the interaction between packaging density and different COB packaging substrates have been conducted, especially regarding the thermal performance of the COB packaging of deep UV LEDs.

LED devices are small, compact, and interiorly complex, making it difficult to accurately test and study with general experimental methods. Owing to the rapid development of computer technology, finite element computer simulation can analyze the temperature distribution the cloud diagram, stress, and pressure distribution inside devices, which has become an important source for research [14,15]. In this study, three COB substrates that are commonly used currently were employed to conduct a finite element simulation analysis of deep UV LEDs with different packaging densities, where the temperature distribution relationship between the COB substrates and the packaging density were analyzed.

2. COB packaging structure of deep UV LED

Deep UV LEDs generally refer to UV LEDs with the center wavelength of luminescence between and 200–280 nm. Because most circulating deep UV LED devices on the market are packaged by the flip UV chips, in our study, we selected the LEDV-F35BT2, a commercialization deep UV LED flip chip by LG Innotek, as the research basis. As shown in Fig. 1, the top and bottom views, as well as the lateral section, are displayed. It is 530 µm × 310 µm in size, 250 µm thick, the distance between the two electrodes is 150 µm, the electrical power is approximately 0.3 W, and the UV radiant power is 2 mW; thus, approximately the entire 0.3 W was calculated as thermal power.

![Fig. 1. Sketch diagram of LG deep UV LED flip chip.](image-url)
The COB packaging structure of the flip-chip deep UV LED is shown in Fig. 2 (a and b). Going from bottom to top, it consists of the substrate layer, copper circuit layer, solder paste layer (bonding layer), and flip chip. According to the different substrate materials, they can be divided into the following two categories: metal and ceramic substrates, as shown in Figs. 2(a) and 2(b), respectively. Metal substrates mainly consist of aluminum and are advantageous because they are mature in technology and low in cost. However, metal is a conductor; while laying the circuit, an insulating layer must be added above the aluminum material, which has a significantly low thermal conductivity. Ceramic substrates, including alumina (Al₂O₃) and aluminum nitride (AlN), are advantageous because they do not require the addition of an insulation layer when laying a circuit owing to the fact that ceramic is a non-conductor; therefore, heat transfer performance is better, but the disadvantage includes a relatively high cost.

3. Establishment and analysis of finite element simulation model

In this study, 1313 COB substrates (size: \(13 \times 13 \times 1 \text{ mm}\)) and the aforementioned LEDV-F35BT2 LG Innotek deep UV LED flip chip were used to establish the simulation model. As shown in Fig. 3, the substrate was 13 mm \(\times\) 13 mm in size and 1 mm thick; the thicknesses of the copper circuit and solder paste layers were 1 OZ (\(\sim 0.035 \text{ mm}\)) and 0.03 mm, respectively. The die bonding zone was 9 mm in diameter, which was located in the middle of the top surface of the substrate, where the insulation layer thickness on the metal substrate was 0.1 mm. In the die bonding zone, different numbers of deep UV LED flip chips were arranged to achieve the existing conventional 5, 7, 10, 15, 20, and 24 W power package, which was further expanded to 36 and 48 W. According to the simulation of the COB deep UV LED temperature distribution with different packaging densities and substrate types, the corresponding limited operating temperature of each COB packaging deep UV LED component was studied.

We defined the packaging density as the ratio of the LED electrical power to the die bonding area as follows:

\[
\rho_f = \frac{P_d}{S_g}
\]

where, \(\rho_f\) represents the packaging density, \(P_d\) refers to the electric power, and \(S_g\) is the die bonding area; thus, the aforementioned packaging power is converted to 0.08, 0.11, 0.16, 0.24, 0.31, 0.38, 0.57, and 0.75 W/mm², respectively. Because the upper part of the chip package generally consists of air or silica gel with extremely low thermal conductivity, more than 90 % of the heat generated by the chip is dissipated by heat conduction, which is carried out layer by layer by the heat sink or radiator. Therefore, the model is simplified accordingly, and we mainly analyzed the heat conduction in the downward direction.

Table 1 presents the thermal conductivity of the packaging materials used and the maximum ultimate temperature that each component can withstand in the long term. Combined with the actual situation, a fixed substrate solder joint temperature of 75 °C was used for this study. In the course of modeling, a constant-temperature plate with a temperature of 75 °C was placed at the bottom of the substrate to simulate a fixed infinite heat sink of 75 °C. The highest temperature of each component was recorded for the simulation analysis, which is usually located in the central region of each component.

3.1. Analysis of COB packaging with aluminum substrate

Fig. 4 (a) presents the temperature distribution of the simulation of a 15 W COB deep UV LED packaging by aluminum substrate, and Fig. 4 (b) presents the change in the maximum temperature of each component of the deep UV LED package by the aluminum substrate COB with the packaging density. As shown in Fig. 4 (b), the temperature of the aluminum substrate is maintained at approximately 75 °C, which is equal to the temperature of the welding spot, while the temperature of the insulation layer increases with increasing package density, which indicates that the heat dissipation bottleneck of the aluminum substrate COB package structure is located on the insulation layer, and directly blocks the longitudinal channel of heat transfer. As shown in Fig. 5, the temperature of the insulation layer between adjacent chips is low, indicating that the insulation layer also restricts the transverse transfer of the heat generated by the chip. In addition, when the packaging density is below 0.31 W/mm², the temperature of each component does not change significantly with the increase in package density; however, after the package density is greater than 0.31 W/mm², the temperature of each component increases approximately linearly with the increase of package density owing to the thermal overlap effect [6,7,10].
When the package density is greater than 0.38 W/mm$^2$, the chip temperature is approximately 130 $^\circ$C, reaching its working temperature limit, which will affect the lifetime of the chip during long-term operations. When the package density is approximately 0.47 W/mm$^2$, the insulation layer reaches its working temperature limit of approximately 130 $^\circ$C, while long-term operations may lead to material denaturation and cause a series of other problems including electric leakage. Therefore, the maximum package density of the COB deep UV LED with an aluminum substrate should be maintained below a packaging density of 0.31 W/mm$^2$ and coupled with a suitable heat dissipation to ensure that the device can operate for long-term stability.

### 3.2. Analysis of COB packaging with ceramic substrate

#### 3.2.1. Analysis of alumina ceramic substrate

Fig. 4 (c) presents the temperature distribution cloud diagram of a 15 W deep UV LED with a COB package by alumina ceramic, and Fig. 4 (d) presents the temperature relationship diagram of various components of the alumina ceramic packaged COB deep UV LED with different packaging densities. As shown in Fig. 4 (d), the temperature distribution is different from the COB package with an aluminum substrate. The temperature of the components from the beginning increases with increasing package density because there is no insulating layer, despite the thermal conductivity of alumina ceramic only being 20 W/(m·K), which can still provide a better lateral cooling channel for chips; thus, considering the thermal overlapping phenomenon from the beginning, the temperature in the central area of components is higher owing to the multiple thermal overlap. When the packaging density is greater than 0.31 W/mm$^2$, the thermal overlap effect is more intense, thus the maximum temperature of each component also rises sharply. In addition, this is also due to the low thermal conductivity of alumina ceramics, which blocks the longitudinal heat dissipation channel of the chip to some extent. Notably, when the package density is below 0.75 W/mm$^2$, each component has not reached its limit working temperature, and can work stably for a long time. However, the packaging density continues to increase and reaches above 0.94 W/mm$^2$, the working life of the chip is predicted to be affected owing to reaching its ultimate working temperature.

#### 3.2.2. Analysis of aluminum nitride ceramic substrate

Figs. 4 (e–f) present the temperature distribution diagram of the 15 W deep UV LED package by the aluminum nitride ceramic, and the temperature variation diagram of each component of the COB deep UV LED package by the aluminum nitride ceramic with the packaging density. According to the tendency in Fig. 10, the temperature of each component shows a similar rising trend with increasing package density, but the rising value is not high. With the increase in the package density from 0.08 to 0.75 W/mm$^2$, each component increased by only approximately 3.7 $^\circ$C. This is mainly because the heat dissipation performance of aluminum nitride ceramics is exceptional, and the thermal conductivity is more than five times that of alumina ceramics. The heat dissipation of the chip does not require transverse heat dissipation channels, thus the thermal overlap effect does not work, and the longitudinal heat dissipation channels can sufficiently meet the heat dissipation of the chips. This is entirely opposite to the aluminum substrate and alumina ceramic substrate, and it is the best in these substrates. The temperature of each component is not affected by the packaging density, and can adapt to a higher packaging density.
Fig. 4. Cloud diagram of temperature distribution of 15 W deep UV LED packaged by different COB substrates and the temperature variation diagram of each component of the deep UV LED packaged by different COB substrates with different packaging densities.

Fig. 5. Temperature variation curves of the axis in different directions on the top surface of different substrates: (a) X-axis, (b) Z-axis.
3.3. Comparative analysis of 15 W COB deep UV LED with three different substrates

To better compare the performance differences of these three COB substrates, we selected the 15 W (0.24 W/mm² packaging density) COB deep UV LED, and the temperature changing curves of the axes (X and Z axes) at the same position of the top surfaces of different substrates (the position of the aluminum substrate packaging COB is the top surface of the insulation layer) were intercepted. The interception positions are shown in Fig. 3. Fig. 5 shows the temperature changing curves of the axes in varying directions of different substrates. As shown in Fig. 5 (a), on the X-axis of the top surface of the insulation layer of the aluminum substrate packaging, COB displays significant temperature changes that occur between high and low peaks and troughs alternately, and different low-temperature troughs in areas near the middle of the insulating layer temperature is higher, which is the overlapping effect caused by heat. The lower troughs indicate the interval between different chips, and the thermal overlap effect is lighter, thus the temperature is lower; however, the higher troughs are at the bottom of the single-chip part between the positive and negative electrode pads, which is closer to the heat source making the temperature relatively higher. The peak temperature does not increase significantly, which indicates that the influence of the thermal overlap effect remains similar. Thus, for the X-axis of the top surface of the alumina ceramic substrate and aluminum nitride ceramic substrate, although the same phenomenon is still observed, it becomes less apparent, which proves that the ceramic provides better longitudinal and transverse heat dissipation channels.

As shown in Fig. 5(b), there is also a significant temperature change between the high and low peaks and troughs in the Z-axis of the insulation layer of the aluminum substrate; however, each peak and trough are at basically the same temperature, which indicates that the chip spacing greater than the X-axis cannot cause a thermal overlap. In contrast, the insulation layer blocked the lateral thermal transfer channel. Similarly, the alumina ceramic substrate also has the same changing trend, but its peak and trough temperatures have more drops than those of the aluminum substrate, and the difference between the peaks and troughs is small, which also proves that alumina ceramic provides a better longitudinal heat transfer channel and a certain transverse heat transfer channel. As for aluminum nitride ceramic substrate, the temperature peaks and troughs become relatively flat, proving that the aluminum nitride ceramic does not only provide sufficient longitudinal, but also transverse thermal conductivity channels.

In summary, to meet the requirements of sterilization efficiency of deep UV LEDs, we need COB packaging technology to achieve higher packaging density to output higher light energy density and UV intensity. There are two types of COB packaging substrates, aluminum and ceramic. The aluminum substrate is advantageous for its low price and mature technology, but should not be used for high packaging density. On the contrary, ceramic substrates are a better choice, but the high cost also limits its use to a certain extent, and there is a significant price difference between alumina ceramic and aluminum nitride ceramic. The former is about the latter 1/10-1/7 [14,15], thus we should choose the appropriate substrate for use according to the specific customer requirements.

4. Conclusion

In this study, the thermal performance of three COB packaging substrates was analyzed based on the COB packaging of a flip-chip deep UV LED, as well as the relationship between the packaging density of the COB packaging deep UV LED and the ultimate working temperature of each component that these substrates can withstand. This study indicates that with a substrate size of 13 mm × 13 mm × 1 mm, when the packaging density of the aluminum substrate is greater than 0.38 W/mm², the chip reaches its ultimate operating temperature. When the packaging density is approximately 0.47 W/mm², the insulation layer reaches the ultimate operating temperature, indicating that the aluminum substrate is not suitable for a packaging density greater than 0.38 W/mm². The alumina substrate meets the requirements indicated in the entire scope of the study, and the ultimate working temperature of the material will not appear. However, according to the trend prediction, it cannot meet the requirement of the 0.94 W/mm² density packaging. This will make its chip reach the limit operating temperature, affecting the reliability of the devices. Aluminum nitride ceramic substrates can meet the packaging requirements of higher packaging density, but its high cost is an important factor to be considered for its large-scale application. The results of this study provide detailed suggestions for researchers or industrial use to select substrates for COB packaging of deep UV LEDs according to different packaging densities, which has high practical application value.

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Declaration of Competing Interest

The authors declared that they have no conflicts of interest to this work.

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