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Research Article

Temperature Distribution Research on Liquid Packaging Structure of Deep UV LEDs

Zhenghao Xia,[1] Zuojie Wen,[2] Bingqian Li,[2] Fei Wang,[1] and Daming Zhang[1]

[1]*State Key Laboratory of Integrated Optoelectronics, College of Electronic Science and Engineering, Jilin University, Changchun 130012, China*
[2]*School of Applied Physics and Materials, Wuyi University, Jiangmen 529020, China*

Correspondence should be addressed to Fei Wang; wang_fei@jlu.edu.cn

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By showing a packaged device model with 2×2 chips, the effects of packaging material, device height, chip spacing, thermal conductivity, and viscosity of silicone oil on temperature distribution of deep ultraviolet (UV) light-emitting diodes (LEDs) were investigated by finite element simulation. The results showed that similar temperature distributions in the horizontal and vertical directions were obtained using different packaging materials including gas, solid, and liquid. The lowest maximum temperature (131.7°C) was obtained with liquid packaging compared to the gas packaging (140.8°C) and solid packing (132.5°C). Accompanied by increasing the device height, the maximum temperature of the liquid packaging structure revealed a more significant drop compared to solid packaging. However, that of gas packaging exhibited a rise and saturation. Larger chip spacing and higher thermal conductivity of silicone oil will dramatically reduce the maximum temperature of the liquid packaging device, and a lower maximum temperature and more uniform temperature distribution were obtained by using a lower viscosity packaging material. Therefore, considering the feasibility of the device process, appropriate liquid packaging structures can be optimized, and the maximum temperature of the liquid packaging structure of 102.8°C has been achieved. Liquid packaging may have a certain impact on the reliability of device sealing due to the current immature technology. For high-power light sources, there may also be a certain impact on their lifespan.

1. Introduction

Deep ultraviolet (UV) light-emitting diodes (LEDs) have been recognized in the commercial field due to their advantages such as energy saving, environmental protection, and long working life [1]. Because of the high energy of deep ultraviolet light with a short wavelength from 200 nm to 280 nm, microorganisms can be destructed in a brief time by exposure to deep ultraviolet light, due to inhibited reproduction by altering the structure of genetic material, for example, DNAs or RNAs. Therefore, deep UV LEDs are expected to be widely used in water purifiers, maternal and child products, air conditioners, refrigerators, etc. [2, 3].

Nowadays, multichip packaging is usually used to obtain high optical power to meet production needs, due to the low output power of single-chip deep UV LEDs. Nevertheless, the accumulation of heat brought by low-efficiency deep UV LED array will sharply increase the junction temperature, which will degrade the quantum efficiency and reliability of deep UV LEDs [4, 5]. A lot of work has been reported to reduce the maximum temperature of deep UV LEDs and suppress the negative effects of rising temperatures. For instance, an optimized packaging density and substrate type were investigated to improve the reliability and life by analyzing the effects on the temperature distribution [6], a novel packaging structure using silicon doped with aluminum nitride nanoparticles was proposed to realize a light extraction efficiency improvement (17.4%) and a chip junction temperature reduction (5.7°C) [7], and a new organosilicon composite material with graphene oxide embedding in the air gap of the bonding interface was prepared to obtain a significant temperature reduction of 34% [8].

However, it is still a huge challenge to suppress the high maximum temperature, and the development of effective

cooling methods is of paramount importance for high-power deep UV LEDs. A liquid packaging structure was devised to reduce the device temperature and improve the reliability and life of deep UV LEDs, by improving thermal conduction through the high thermal capacity liquid silicone oil in the thermal fluid flow field, and an optical power enhancement with 70.7% and a thermal resistance reduction with 30.3% were achieved [9–11]. At the same time, the liquid packaging structure can prevent the corrosion of metal by moisture and oxygen effectively, because of the chip cladding with silicone oil. Indeed, there are still few deep analyses on the effect of the liquid packaging structure on the temperature distribution, although a great advantage in reducing the device temperature of the liquid packaging structure has been predictable.

In this paper, a finite element simulation has been applied to obtain temperature distribution mappings by changing the packaging structures and packaging processes. The effects of packaging material, device height, chip spacing, thermal conductivity, and viscosity of silicone oil of liquid packaging structure on temperature distribution of deep ultraviolet (UV) light-emitting diodes (LEDs) have been systemically studied.

2. Deep UV LED Structures and Computational Method

Three commonly used deep UV LED packaging structures have been described, which are shown in Figure 1, (a) gas packaging (conventional flat lens type) UV LED, (b) solid packaging UV LED, and (c) liquid packaging UV LED [12–14]. As shown in Figure 1, the three structures are consisting of substrate, chips, and flat lens, the chips are attached to the substrate and sealed by the flat lens, and the filling material in the sealed interspace is gas (structure a), solid (structure b), and liquid (structure c), respectively.

To investigate the temperature distributions of different structures in detail, ICEPAK simulation software has been used to establish a simulation model of deep UV LED, as described in Figure 2. From bottom to top, the substrate, insulating layer, copper layer (circuit layer), solder paste layer (bonding layer), LED chips, filling material, and lens are set up in sequence. The insulating layer was set between the substrate and the circuit layer, due to the electric conduction of the aluminum substrate with high thermal conductivity. Four deep UV LED chips were employed and attached to the circuit layer by bonding layer, and the spacing lengths between chips were set to 0.5 mm, the electric power and wall-plug efficiency were set to 3 W and 20%, respectively, and the overall sizes of the model were 4 mm in length and width and 2.38 mm in height (4 mm length, 4 mm width and 2.38 mm height). Besides, the thermal conductivity and dimensions of packaging components are shown in Table 1.

As we know, the thickness of the active layer is nanometer scale which can be negligible compared to that of the UV LED chip, and the active layer is close to the chip bottom attributed to the flip chip structure of the UV LED chip. So, a sheet heat source was placed at the bottom of the chip to simulate the heating of the chip simply. Then, to assist the heat dissipation of the UV LED module, an external heat sink with a maximum temperature of 75°C has been introduced. Hence, a fixed infinite heat sink with 75°C was set at the bottom of the substrate, and the corresponding environment temperature was set to 75°C, during the simulation.

3. Temperature Distributions of Three Packaging Structures

The influence of three packaging structures on temperature distribution has been investigated; silicone oil and fluorine resin were employed as the filling material of liquid packaging and solid packaging, respectively, and the thermal conductivities of silicone oil and fluorine resin were adopted as the same value of 2.3 W/(m·K), and the default value of silicone oil viscosity was 1000 cP.

3.1. Mapping of Temperature Distribution. As we know, the maximum temperature of LED chip is usually at the center of the chip and that is a key concern of the chip's service life. Figure 3(a) shows the temperature distribution of the UV LED module with liquid packaging. Due to the short spacing between the chips, the thermal field superposition of the four-chip array exhibited peaks and a valley temperature distribution in our simulation, and four temperature peaks appeared at the noncentral position of the chips. Because of the symmetrical distribution of the four chips, the same maximum temperatures at similar positions on chips have been observed, and the position of one of the maximum temperatures was labeled as I point in the figure. To further investigate the temperature distribution in-depth, three specific line spectrums of temperature along the x-axis are delineated in Figure 3(b). The line spectrums cover the left edge to the right edge of the chips, and lines A, B, and C were across the middle of chips, I point, and middle of the array, respectively. Due to the superposition of the thermal field, the three curves were all composed of two peaks and one valley. The temperature differences between the peaks and valleys of lines A and B are the same value of 3.1°C, while the difference in line C is only 0.3°C. Then, the temperature distributions of gas packaging and solid packaging similar to liquid packaging of UV LED were obtained, and the maximum temperatures of gas packaging, solid packaging, and liquid packaging were calculated to be 140.8, 132.5, and 131.7°C, respectively. Due to the higher thermal conductivity and fluid heat transfer of the liquid packaging structure, the lowest chip temperature has been achieved.

3.2. Device Height on Temperature Distributions. Although the liquid packaging structure achieved the lowest maximum temperature compared to the gas packaging and solid packaging, however, the maximum temperature of the liquid packaging structure of the above is only 0.8°C lower than that of the solid packaging. Herein, to further exert the advantages of liquid packaging in fluid heat transfer and high thermal conductivity to obtain a lower maximum temperature, the influence of device heights (H) on the

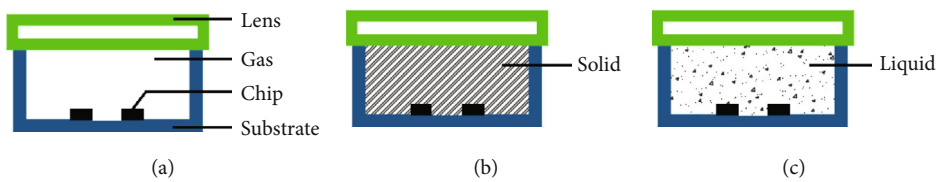


Figure 1: Deep UV LED structures of (a) gas packaging, (b) solid packaging, and (c) liquid packaging.

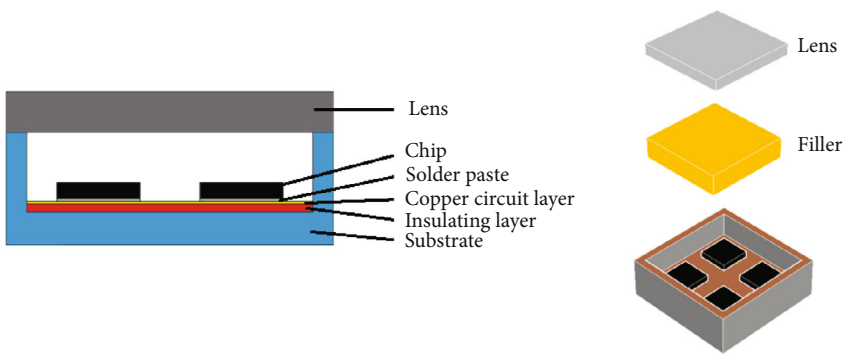


Figure 2: Simulation model of deep UV LED.

Table 1: Thermal conductivities and dimensions of packaging components.

Packaging components	Materials	Sizes (mm)	Thermal conductivities (W/(m·K))
Substrate	Al	4*4*0.4	237
Insulating layer	——	3.5*3.5*0.1	0.25
Circuit layer	Cu	3.5*3.5*0.035	401
Solder paste	SnAgCu	1*1*0.03	60
Chip	Sapphire	1*1*0.2	50
Lens	Glass	4*4*0.5	0.21

maximum temperature of chips has been investigated, and the results are displayed in Figure 4.

For gas packaging, the maximum temperature of chips increases with the increase of H and reaches the maximum value when H is 2.88 mm and then is almost unchanged after that. Because of the low thermal conductivity of gas, it is more difficult to conduct heat with increasing H, so the maximum temperature increases at the first and then attributed to heat convection of gas; the change of maximum temperature is almost negligible with the following increasing of H. For solid packaging, the maximum temperature decreases, and the decline rate gets slower as H increases. The main reason is that heat is easily transferred to the upper surface of the device with a small H, so increasing H is helpful for heat dissipation. However, for a higher H, it is difficult for heat to transfer to the upper surface because of the low thermal conductivity of fluorine resin, so the maximum temperature declines more slowly. For liquid packaging structure, the maximum temperature drops rapidly at first and then drops slowly as H increases, which is similar to solid packaging. However, compared to solid packaging, the maximum temperature of liquid packaging structure is lower from 0.2°C to 1.9°C as H increases from 1.88 mm to 3.88 mm. Attributed to more efficient heat convection of silicone oil, the maximum temperature of liquid packaging structure shall be lower with higher H.

4. Temperature Distributions on Packaging Processes of Liquid Packaging

As mentioned above, the liquid packaging structure has the lowest maximum temperature compared with gas packaging and solid packaging. Therefore, further research on the influence of packaging processes of liquid packaging on temperature distribution needs to be conducted in detail, to obtain an optimized liquid packaging process.

4.1. Chip Spacing on Temperature Distributions. Figure 5 shows the temperature distributions of chip spacing of 1.5 mm in (a), 0.5 mm in (b), and 0.1 mm in (c) and the variation of maximum temperature with chip spacing. As can be seen from Figures 5(a)–5(c), the heat is concentrated on

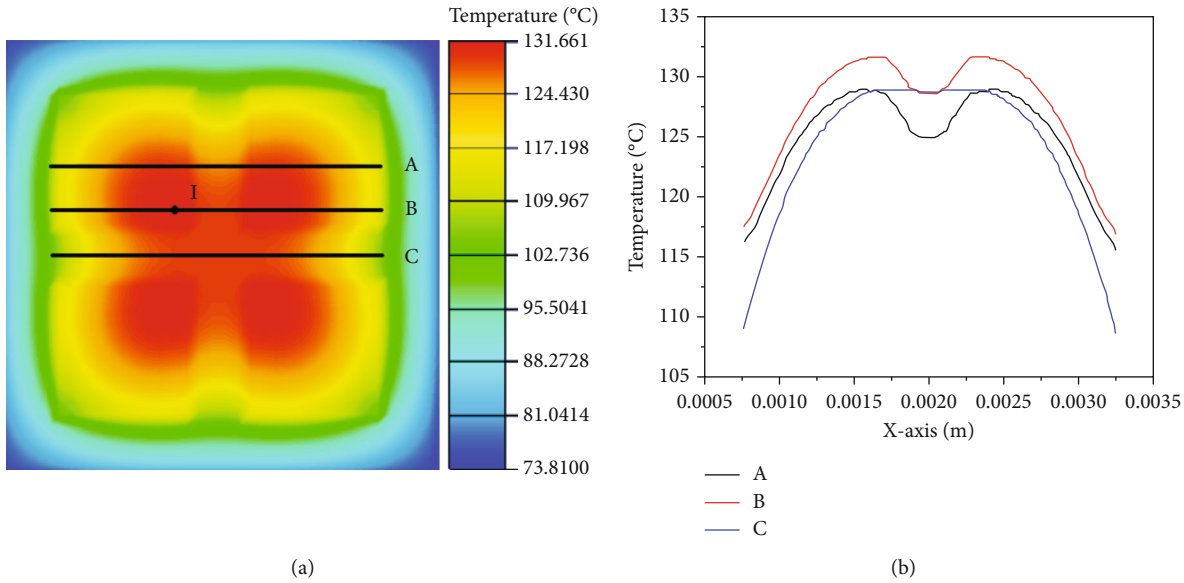


Figure 3: (a) Temperature distribution and (b) line spectrums along the x-axis of UV LED module with liquid packaging.

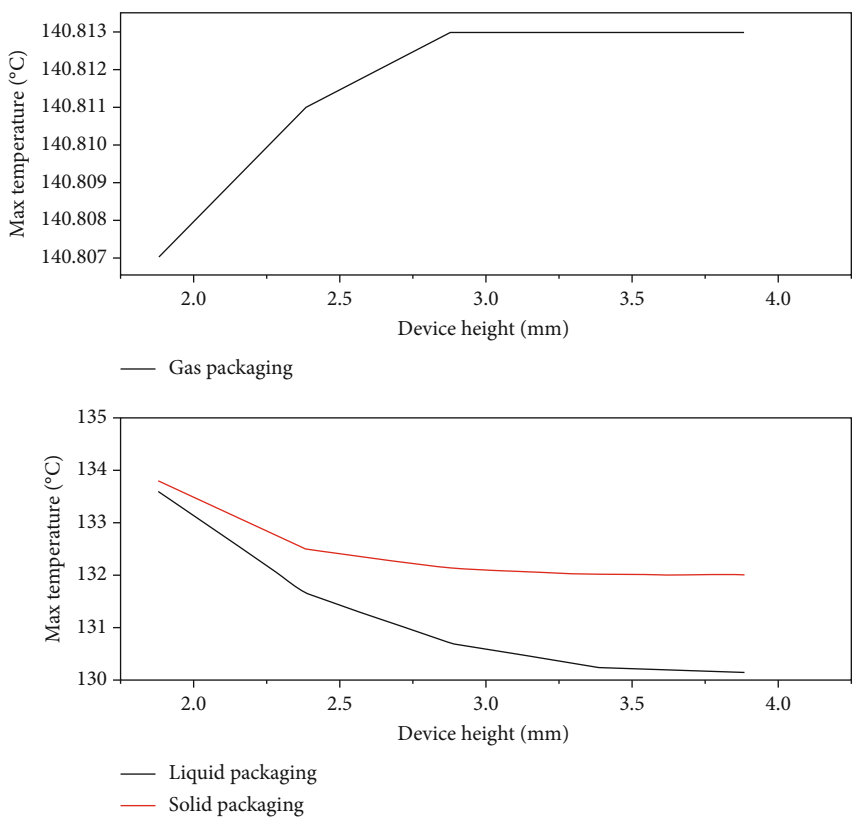
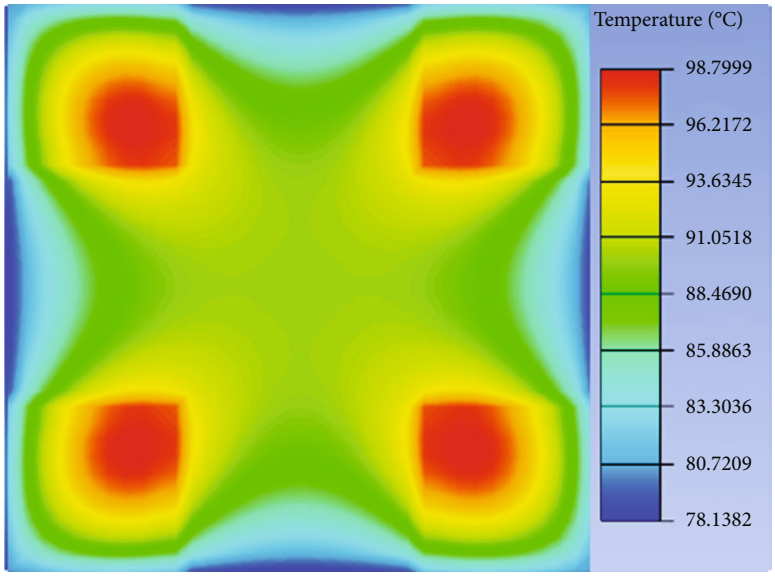
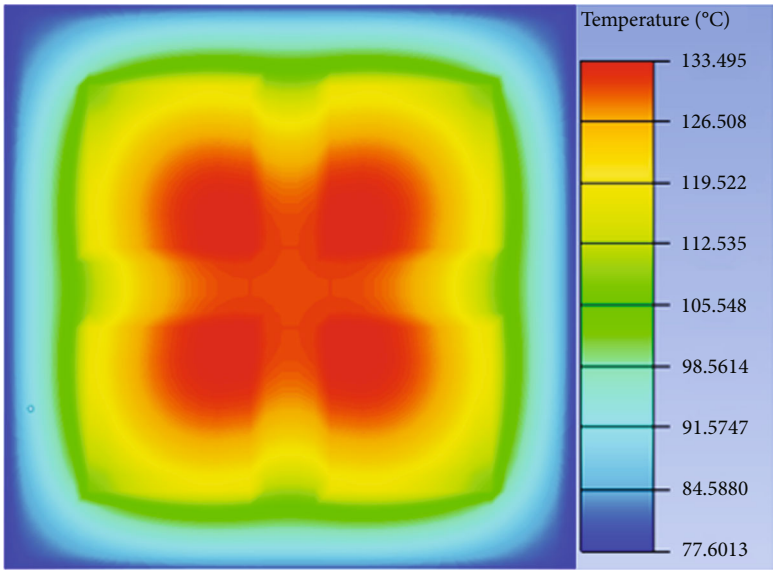


Figure 4: Maximum temperature vs. device heights (H) of three packaging structures.

the four LED chips with large chip spacing and tends to accumulate towards the center of the device with small chip spacing, due to the heat superposition of the four chips [15]. In Figure 5(d), along with the decreasing of chip spacing, the maximum temperature of chips rises rapidly, the value of that is 98.8°C at the chip spacing of 1.5 mm and rises to 150.1°C at 0.1 mm, and an increment of 51.3°C has been obtained. Due to the accumulation of heat, the thermal resistance of four chips is coupled with small spacing, which leads to an increase in the maximum temperature. Hence, a lower maximum temperature can be obtained with larger chip spacing in multichip packaging; however, considering

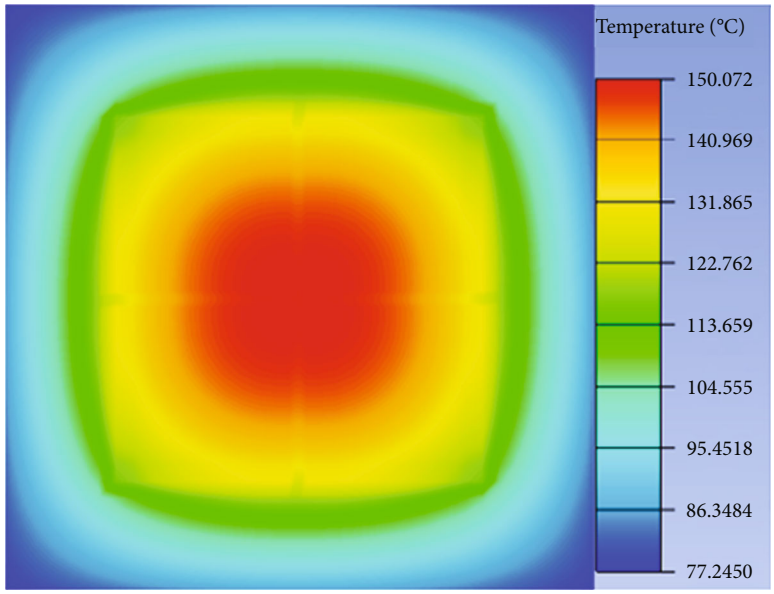


(a)

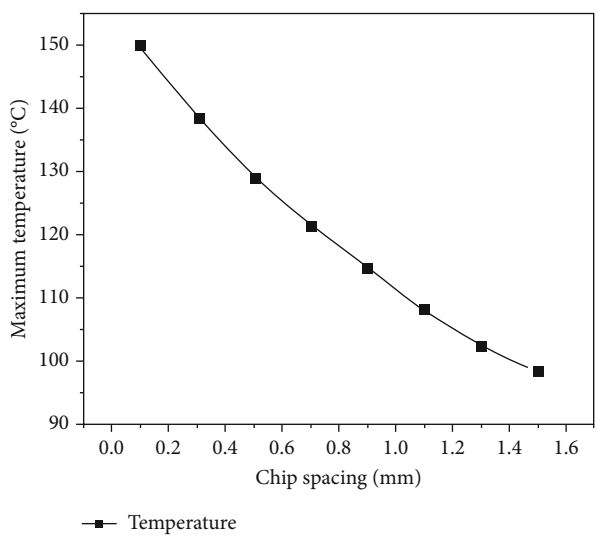


(b)

Figure 5: Continued.



(c)



(d)

Figure 5: Temperature distributions of chip spacing of 1.5 mm (a), 0.5 mm (b), and 0.1 mm (c). (d) Variation of maximum temperature with chip spacing.

the device cost and process feasibility, too large chip spacing is difficult to utilize in actual applications.

4.2. Viscosity of Silicone Oil on Temperature Distributions. In general, the higher viscosity of silicone oil corresponds to poor fluidity, which will weaken the heat transfer. The viscosity coefficient of silicone oil is generally between 0.65 cP and 100 cP in the temperature range 25-100°C; hence, we adopt a silicone oil viscosity range of 0 cP-100 cP for analysis in this study.

As depicted in Figure 6(a), the maximum temperature of the chips and the difference between the maximum temperature of chip and the temperature at the top of the silicone oil increase sharply with the viscosity increase in the range of 0-10 cP, due to the higher efficient heat transfer of silicone oil with lower viscosity. However, attributed to the worse liquid fluidity with a viscosity over 10 cP, the heat is more difficult to transfer, which would lead to a slow rise as the viscosity increases. To further realize the temperature distributions with different viscosities, the cross-sectional temperature distributions at I point with 0.65 cP and 100 cP are illustrated in Figures 6(b) and 6(c), respectively. At low viscosity, a uniform temperature distribution has been achieved, due to the better heat transfer. In turn, because of the worse heat transfer, the heat is concentrated near the chip, and a higher maximum temperature would be obtained at high viscosity. It can be predicted that a temperature distribution will be like that of solid packaging with higher viscosity silicone oil. Consequently, by adopting low-viscosity silicone oil, the maximum temperature can be

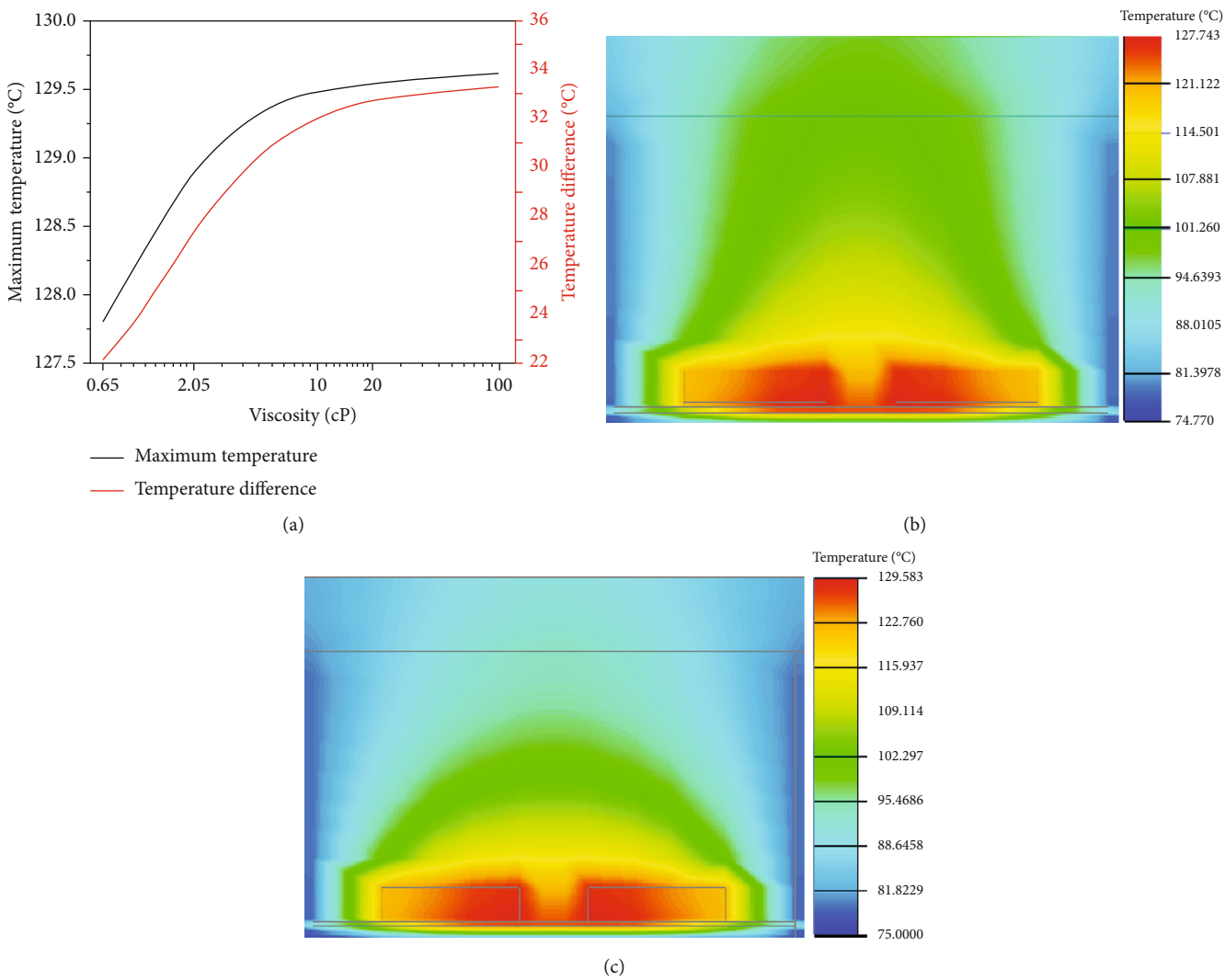


Figure 6: (a) The maximum temperature of the chips and the difference between the maximum temperature of the chip and the temperature at the top of the silicone oil. The cross-sectional temperature distributions at I point with 0.65 cP (b) and 100 cP (c).

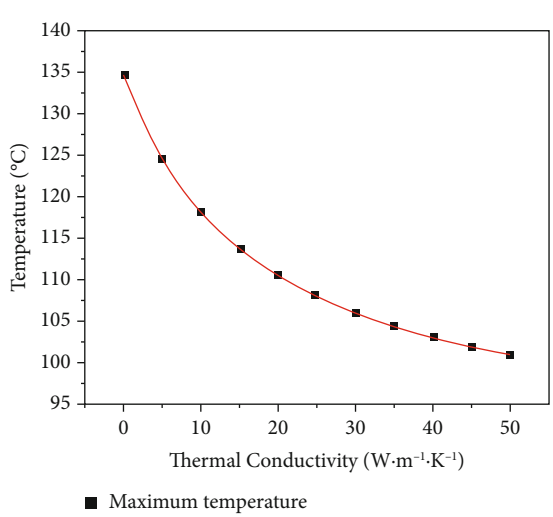


Figure 7: The maximum temperature vs. thermal conductivity of silicone oil.

effectively reduced, and a more uniform temperature distribution can be obtained, which will reduce the aging of packaging materials effectively.

4.3. Thermal Conductivity of Silicone Oil on Temperature Distributions. Since the heat generated from chips can be transferred to the lens through the silicone oil, and then to the air for dissipation, the temperature distribution should be affected by the thermal conductivity of silicone oil. At present, the thermal conductivity of ordinary silicone oil is between 0.13 and 2.3 W/(m·K), and a higher thermal conductivity, the value of that is 32 W/(m·K) and higher, can be achieved by doping graphene in silicone oil. We have adopted the thermal conductivity of silicone oil in the range of 0-50 W/(m·K) to investigate the maximum temperature dependence on the thermal conductivity of silicone oil, and the results are shown in Figure 7.

From Figure 7, the temperature dropping rate is significantly different in different thermal conductivity ranges; a slower and slower temperature dropping can be achieved

as the thermal increased from 0 to 50 W/(m·K). We have selected five distinct thermal conductivity intervals of 0-5, 5-10, 10-20, 20-30, and 30-50 W/(m·K), respectively, and the fitted values of the falling slope of maximum temperature curve are 2.08, 1.26, 0.75, 0.45, and 0.26 (°C·m·K)/W, corresponding to the aforementioned thermal conductivity intervals. It is foreseeable that a slower drop in the maximum temperature of the chip will be achieved while continuing to increase the thermal conductivity of silicone oil over 50 W/(m·K). Hence, the high thermal conductivity of silicone oil can effectively reduce the maximum temperature of chips, but the effect on temperature is almost negligible as the thermal conductivity of silicone oil continues to increase over a specific value, such as 50 W/(m·K).

Finally, based on the effects of packaging structures and processes on temperature distributions, with a view to the practical application of the deep UV LED device, the device height of 2.38 mm, chip spacing of 0.5 mm, silicone oil viscosity of 60 cP, and silicone oil thermal conductivity of 30 W/(m·K) were introduced to the simulation on liquid packaging device, and the maximum temperature of the chips that is only 102.8°C has been obtained. Meanwhile, by adopting analogical device parameters, the maximum temperatures of gas packaging and solid packaging were carried out as 140.8°C and 132.5°C, respectively.

5. Conclusions

In summary, we investigated the temperature distributions of four-chip packaging deep UV LEDs on packaging structure and process in detail via ICEPAK simulation software. Like gas packaging and solid packaging, the temperature distribution of liquid packaging structure filled with silicone oil has shown a peak and valley distribution with four peaks appearing at the noncentral position of the chips and the lowest maximum temperature has been obtained for the liquid packaging. Increasing the device heights, the maximum temperature of the liquid packaging structure revealed a faster drop compared to that of solid packaging; in turn, that of gas packaging obtained an increment. Aiming at liquid packaging, a lower maximum temperature can be obtained with larger chip spacing, lower viscosity of silicone oil, and lower thermal conductivity of silicone oil. Taking into account the practical applications of deep UV LEDs, an excellent maximum temperature of the chips 102.8°C has been achieved with optimized structure and process of liquid package; however, the corresponding maximum temperatures of gas packaging and solid packaging were 140.8 and 132.5°C. Compared to gas packaging and solid packaging, the liquid packaging structure filled with silicone oil of high thermal conductivity and low viscosity can markedly reduce the maximum temperature of the chips. However, due to the small size of the device and the immature packaging technology, liquid packaging is currently quite challenging. The specific implementation process requires continuous research in the future.

Data Availability

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest.

Authors' Contributions

Daming Zhang mainly provided a lot of assistance in reviewing and revising the first draft of the paper. Specifically, it includes organizing and suggesting the internal logic of the article, determining and summarizing the analysis results, and modifying the language.

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