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Study on the influences of the substrate parameters for thermal spreading resistance of light emitting diode

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The life of light emitting diode (LED) has a great relationship with its thermal resistance. As a part of the total thermal resistance, thermal spreading resistance may also affect the reliability of LED. To study the influence of LED packaging substrate for thermal spreading resistance, this article analyzes the influence of different parameters for thermal spreading resistance of single heat source. Results show that the thermal conductivity, the thickness of substrate and the heat source area has great influence on thermal spreading resistance. But the convection coefficient is not so important. And the more the heat source deviates from the center of substrate, the greater the thermal spreading resistance will be. Secondly, based on LED devices with direct bond copper ceramics (DBC) substrate, thermal spreading resistance with two heat transfer layers are analyzed by analytical solution and simulation. The influences of different thickness of copper and ceramics for thermal spreading resistance and total thermal resistance are analyzed. Results show that with the increase of the thickness of copper and ceramics, the thermal spreading resistance and the total thermal resistance are decrease, and the effect of copper is more apparent. So the reasonable design of packaging substrate for LED packaging can reduce the thermal resistance and improve the performance of LED heat dissipation.

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Keywords: Thermal spreading resistance, LED, Substrate, Simulation

1. Introduction

Compared with the traditional light source, LED shows many advantages, such as high luminous efficiency, low power consumption, long service life and environment friendly [1]. With the progress of chip technology, high power LED is forming vertical chip, flip chip and photonic crystals [2-4]. But, LED luminous efficiency can only reach 10% to 20%, the remaining 80% to 90% of the energy is converted into heat [5], which will increase the junction temperature of chip.

The heat dissipation ability of LED devices is affected by many factors, including the packaging structure, LED chip structure, thermal interface materials and cooling conditions. The thermal resistance of LED is composed of a number of components. As a part of the total thermal resistance, thermal spreading resistance occurs in the heat transfer channel, where heat transfer area is changed. Yovanovich et al. [6] analyzed the thermal spreading resistance of single heat source and the solving formula was deduced. Dong et al. [7] proved that there existed thermal spreading resistance on LED substrate based on the definition of Yovanovich [6] through calculation and finite element simulation. Luo et al. [8] considered the thermal spreading resistance with upper and lower substrate surfaces, and provided the solution formula. Actually a substrate may have more than one heat source, but there is no specific formula to solve the thermal spreading resistance of multiple heat source. Yun et al. [9] proposed a method of converting multi-heat sources to a single heat source. But the method is restrictive with the side length of heat source and the distance between heat sources. Cheng et al. [10] analyzed the total thermal resistance by optimizing the distribution of multi-chip positions. Yin et al. [11] analyzed the effects of void ratio in die attach layer on the thermal spreading resistance.

In this paper, the effect of different factors for thermal spreading resistance of single heat source is studied in detail. The thermal spreading resistance of a typical copper bonded to ceramics substrate packaged LED is analyzed. Combined with the compound flux channel theory of thermal spreading resistance, Simulation analysis is used to analyze the effect of different substrate thickness to thermal spreading resistance and total thermal resistance.

2. Experiment results

The single LED chip pacikaging model is established as Fig. 1, consisting of GaN, sapphire, die-attach layer and the substrate. Because the heat transfer area is change at the substrate, there exists thermal spreading resistance based on the definition of thermal spreading resistance. The total thermal resistance can be defined as equation (1).

$$R_T = R_{1D} + R_S \tag{1}$$

Where R_s is thermal spreading resistance and R_{1D} is the one-dimensional thermal resistance defined as equation (2)

$$R_{1D} = \sum_{i=1}^{N} \frac{t_i}{k_i A} + \frac{1}{hA} \tag{2}$$

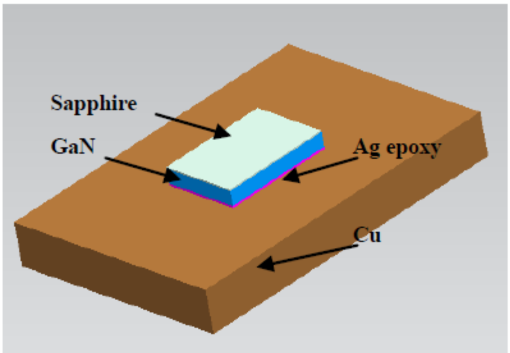


Fig. 1. LED structure model

As is shown in Fig. 2, the LED is packaged with DBC substrate. The heat transfers through the copper and the ceramics to the air. The substrate consists of copper and ceramic. The surface area of copper is 83.5 mm^2, and the surface area of ceramic is 324 mm^2. Material thickness and thermal parameters as is shown in Table 1.

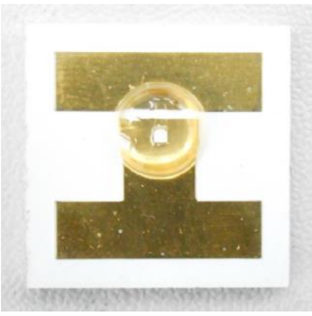


Fig. 2. LED devices with DBC substrate

Table 1. Composition and thermal parameter of LED devices

composition	lens	chip	Ag epoxy	copper	ceramic
Thickness (mm)	/	0.16	0.02	0.07	1
Thermal conductivity (W/mK)	0.1	180	30	389	30

The heat transfer area is changed between the chip and the substrate. So the thermal spreading resistance will be caused here. The total thermal resistance of two LED devices is tested by T3Ster as shown in Fig. 3. Experiments results and calculated thermal resistance as shown in Table 2.

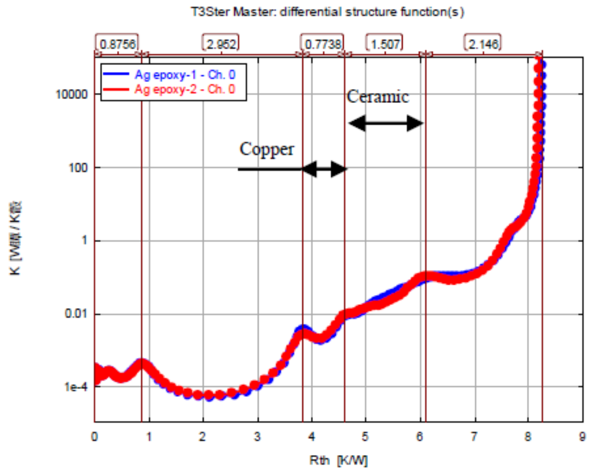


Fig. 3. Thermal resistance of LED device with DBC substrate

Table 2. Thermal resistance of HP-LED module

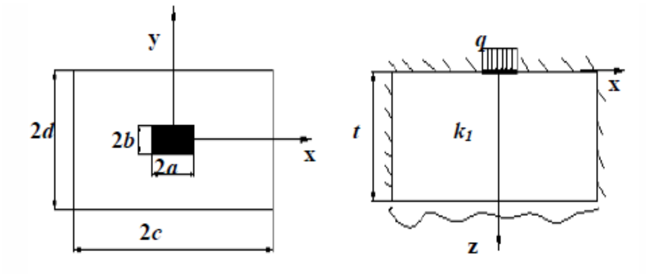
	Copper	Ceramic
Thermal resistance of material (K/W)	0.002	0.1
Thermal resistance by T3Ster test (K/W)	0.774	1.507

The Table 2 and Fig. 3 show that the thermal resistance of substrate is 2.28 K/W . The thermal resistance of copper and ceramic is 0.002 K/W and 0.1 K/W calculated by equation (2). So the thermal spreading resistance is 2.18 K/W , and the most part of substrate thermal resistance is thermal spreading resistance.

3. The influence factors of thermal spreading resistance

3.1 Heat source located in the center of heat substrate

As shown in Fig. 4, the heat source is located in the center of heat substrate. The thermal spreading resistance can be expressed as equation (3) [6].



(a) (b)

Fig. 4. Single heat source model with center position
(a) top view; (b) side view

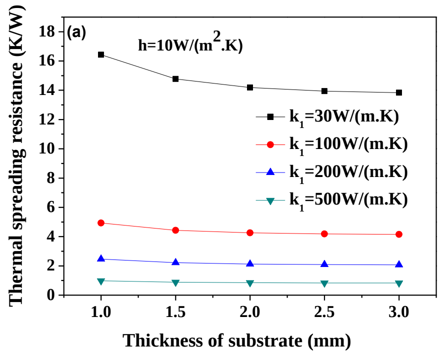
$$R_s = \frac{1}{2a^2 c\, d k_1}\sum_{m=1}^{\infty}\frac{\sin^2(a\delta_m)}{\delta_m^3}\cdot\varphi(\delta_m)$$
$$+\frac{1}{2b^2 c\, d k_1}\sum_{n=1}^{\infty}\frac{\sin^2(b\lambda_n)}{\lambda_n^3}\cdot\varphi(\lambda_n) \quad (3)$$
$$+\frac{1}{a^2 b^2 c\, d k_1}\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\frac{\sin^2(a\delta_m)\sin^2(b\lambda_n)}{\delta_m^2\lambda_n^2\beta_{m,n}}\cdot\varphi(\lambda_n)$$

where

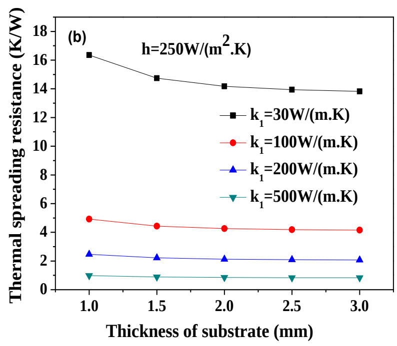
$$\varphi(\zeta)=\frac{(e^{2\zeta t}+1)\zeta-(1-e^{2\zeta t})h/k_1}{(e^{2\zeta t}-1)\zeta+(1+e^{2\zeta t})h/k_1} \quad (4)$$

Where ζ is replaced by δ_m, λ_n or $\beta_{m,n}$ and $\delta_m = m\pi/c$, $\lambda_n = n\pi/d$, $\beta_{m,n}=\sqrt{\delta_m^2+\lambda_n^2}$. The q is heat flux, k_1 is the thermal conductivity, h is the convection coefficient and t is the thickness of substrate.

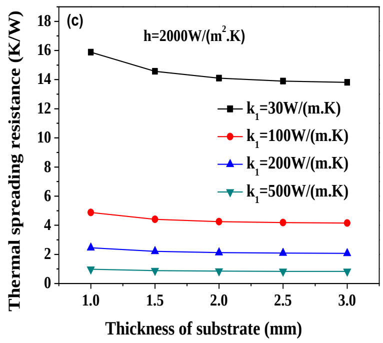
From the solving equations, the thermal spreading resistance is affected by seven parameters of a, b, c, d, k_1, t and h. According to the actual LED device size, the substrate and heat source sizes are fixed as $a=b$ =0.5 mm and $c=d$ =5 mm. The influence of h, k_1, t for thermal spreading resistance are analyzed with Matlab programming.



(a)



(b)



(c)

Fig. 5. Influence of parameter h, k, t for thermal spreading resistance (a) Convection coefficient of 10 W/(m²·K); (b) Convection coefficient of 250 W/(m²·K); (c) Convection coefficient of 2000 W/(m²·K)

Fig. 5 illustrates the thermal spreading resistance affected obviously by the thermal conductivity of substrate. The thermal spreading resistance decreased greatly with the increase of k_1. When the thickness of substrate t less than 1.5mm, the thermal spreading resistance decreased fast with the increase of t. When the thickness of substrate t greater than 1.5mm, the thermal spreading resistance decreased slower with the increase of t. The difference of thermal spreading resistance is small with the convection coefficient changed from 10 $W/(m^2\cdot K)$ to 2000 $W/(m^2\cdot K)$.

As the thermal spreading resistance is caused by the difference of heat transfer area of heat source and substrate, it is necessary to analyze the heat transfer area. The other parameters are defined as k_1 =389 W/(m·K) , h =2000 W/(m^2 · K) and t =1mm. The heat source shape is square and the area of substrate is 100 mm^2 . The relation between the different heat sources area and thermal spreading resistance is shown in Fig. 6.

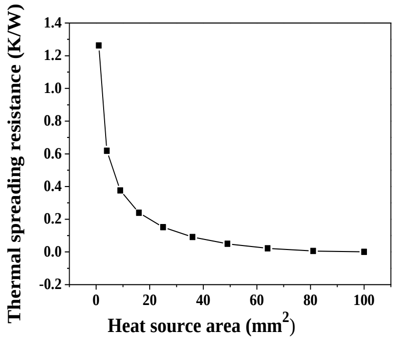


Fig. 6. Influence of heat source area for thermal spreading resistance

Fig. 6 represents that R_s decreases rapidly with the increase of the heat source area when the heat source area is less than 16 mm^2 . The R_s decreases slowly with the increase of the heat source area when the heat source area is greater than 16 mm^2 . And the R_s is close to zero when the heat source area is equal to the contact substrate.

3.2 Eccentric heat sources

The thermal spreading resistance is analyzed detailed with the heat source located in the center of substrate, but the LED chip is not always located at the center of substrate. It is necessary to research the influence of heat source position for the thermal spreading resistance. Fig. 7 shows the single heat source at any position. And the thermal spreading resistance can be expressed as follows equation (5) [12]:

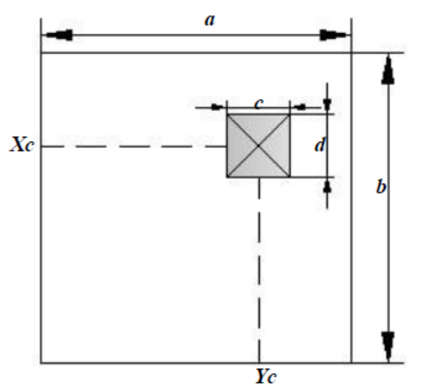


Fig. 7. General heat source position model

$$R_s = \frac{2}{abc^2k_1}\sum_{m=1}^{\infty}\frac{\cos(\lambda_m X_c)\sin(\frac{1}{2}c\lambda_m)}{\lambda_m}\cdot\varphi(\lambda_m)+\frac{2}{abd^2k_1}\sum_{n=1}^{\infty}\frac{\cos(\delta_n Y_c)\sin(\frac{1}{2}d\delta_m)}{\delta_n}\cdot\varphi(\delta_n)+\frac{4}{abc^2d^2k_1}\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}A_{mn}\frac{\cos(\lambda_m X_c)\sin(\frac{1}{2}c\lambda_m)\cos(\delta_n Y_c)\sin(\frac{1}{2}d\delta_m)}{\lambda_m\delta_n}\cdot\varphi(\beta_{mn}) \tag{5}$$

Where

$$A_m = \frac{2\{\sin([(2X_c+c)/2]\lambda_m)-\sin([(2X_c-c)/2]\lambda_m)\}}{\lambda_m^2} \tag{6a}$$

$$A_n = \frac{2\{\sin([(2Y_c+d)/2]\delta_n)-\sin([(2Y_c-d)/2]\delta_n)\}}{\delta_m^2} \tag{6b}$$

$$A_{mn} = \frac{16\cos(\lambda_m X_C)\sin(\frac{1}{2}\lambda_m c)\cos(\delta_n Y_C)\sin(\frac{1}{2}\delta_n d)}{\beta_{mn}\lambda_m\delta_n} \tag{6c}$$

The heat dissipation substrate is assumed as axi-symmetric graphic as Fig. 8. To compare the effect of different heat sources positions for the thermal spreading resistance, different heat source position are shown in Fig. 8. The origin of coordinates is defined in the lower left corner, the heat source center coordinates and the results of thermal spreading resistance are listed in Table 3:

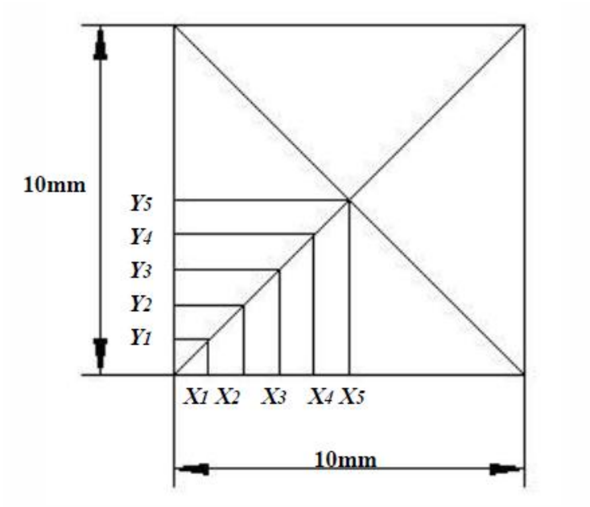


Fig. 8. Different eccentric heat source

Table 3. Results of thermal spreading resistance with different heat source position

	c=1	*c=2*	*c=3*	*c=4*	*c=5*
Xc/mm	1	2	3	4	5
Yc/mm	1	2	3	4	5
Rs/K/W	2.619	1.854	1.495	1.323	1.271

From Table 3, the thermal spreading resistance is affected greatly by the heat source position. And thermal spreading resistance will be increased when the center distance between the heat source and the substrate is increased. So the heat source should be placed on the center of substrate for LED packaging design.

4. Thermal spreading resistance of DBC substrate

Relative to the heat source, copper and ceramics are both heat transfer layers. This would need to study the thermal resistance with compound flux channels. The two heat transfer layer model is established as shown in Fig. 9. The solution equation of the thermal spreading resistance is the same as the equation (3) [12] except the $\varphi(\zeta)$ as equation (7).

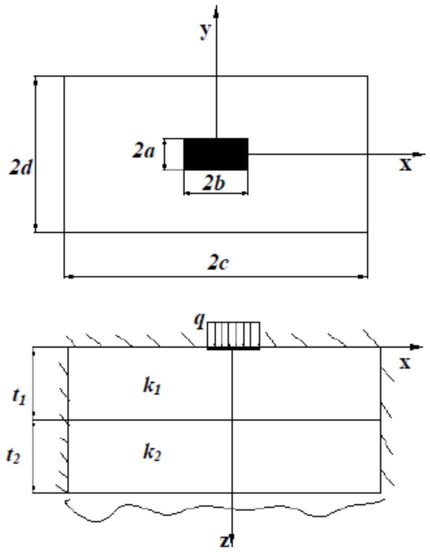


Fig. 9. Two heat transfer layer model

$$\varphi(\zeta)=\frac{(\alpha e^{4\zeta t_1}+e^{2\zeta t_1})+\rho(e^{2\zeta(2t_1+t_2)}+\alpha e^{2\zeta(t_1+t_2)})}{(\alpha e^{4\zeta t_1}-e^{2\zeta t_1})+\rho(e^{2\zeta(2t_1+t_2)}-\alpha e^{2\zeta(t_1+t_2)})} \quad (7)$$

where

$$\rho=\frac{\zeta+h/k_2}{\zeta-h/k_2}, \qquad \alpha=\frac{1-\kappa}{1+\kappa}$$

Where $\kappa=k_2/k_1$, the upper heat transfer layer is copper and the lower is ceramic and k_1 =389 W/(m·K), k_2 =30 W/(m·K). Then the influence of t_1 and t_2 for R_s are analyzed as shown in Fig. 10.

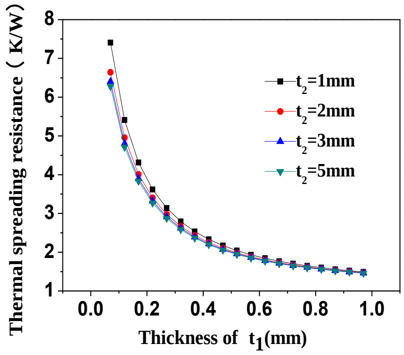


Fig. 10. Influence of two heat transfer lawyer thickness to thermal spreading resistance

First of all, if the substrate is only consist of ceramic, the R_s is 17.84 K/W calculated by equation (3) and (4) with the thickness of t =1mm. As shown in Fig. 10, by adding a heat transfer layer with high heat conductivity, the R_s can be decreased quickly. The R_s decreases quickly with the increase of t_1 when it is less than 0.2 mm. In addition, the R_s can decreases slowly with the increase of t_2 .

The equation (7) is confined to two equal contact area of heat transfer layer and the heat source is located in the center of the substrate. But the LED devices has different contact area between copper and ceramics substrate, and the chip is not located in the center of the substrate. To study the influence of copper clad substrate thickness for total thermal resistance, ANSYS is used to do simulation with different thickness of copper and ceramic. The finite element model of LED is established as shown in Fig. 11.

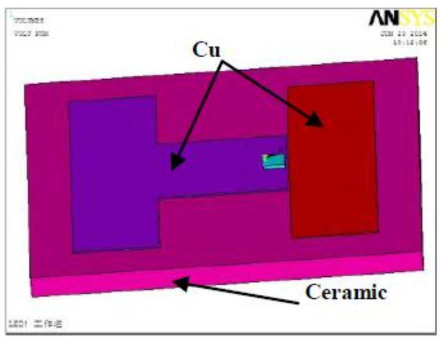


Fig. 11. Finite element model of LED device with DBC substrate

For the boundary conditions and loads, the thermal power is 0.8W (Electric power minus the optical power) and the temperature of substrate bottom surface is 25 ℃. Different thickness of ceramic and copper are analyzed.

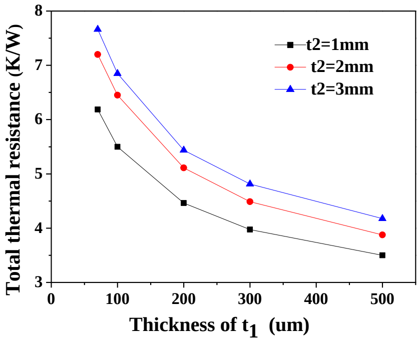


Fig. 12. LED thermal resistance with different thickness of copper and ceramic

Fig. 12 shows that with the increase of the thickness of copper, the total thermal resistance shows a trend of decrease. The total thermal resistance is 6.2 K/W when t_1=70 um and t_2=1mm which is in accordance with the tested result 6.1 K/W in Fig. 3. And the thickness of copper has a greater influence on the total thermal resistance. Because the conductor resistance is increased with the increase of substrate thickness, which mean the decrease part of total thermal resistance is primarily the thermal spreading resistance. The optimal thickness of copper and ceramics are 200 μm and 2 mm respectively, aiming at this kind of LED packaging structure, which is consistent with calculation results by solution formulas. Therefore, it can effectively reduce the thermal spreading resistance and the total thermal resistance by optimizing the cooling substrate structure and size.

5. Conclusion

The single heat source model is established in this paper to analyze the influence of related parameters for thermal spreading resistance. Results show that the thermal conductivity of substrate, the thickness of substrate and the heat source area has a great influence on the thermal spreading resistance. But the effect of convection coefficient on thermal spreading resistance is not obvious. Then combined with the DBC substrate LED devices, the thermal spreading resistance of compound flux channels model is analyzed by matlab calculation and ANSYS simulation. The results show the total thermal resistance can be reduced by increasing the thickness of the copper and the decrease of ceramic layer thickness adequately, and the effect copper thickness is more apparent. It will benefit the LED packaging structure design.

Acknowledgments

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