Effect of Shell Temperature on Thermal Resistance and Junction Temperature for Power Diode

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Abstract. Accurate measurement of junction temperature can avoid thermal failure of diode. During aging test, junction temperature should be indirectly calculated by testing its thermal resistance. In this paper, junction-to-case thermal resistance ($R_{\text{thjc}}$) of XX diode is tested by T3ster based on transient dual interface method. Its $R_{\text{thjc}}$ is about 1.23K/W at 25℃ and contains PN junction thermal resistance, metal shell thermal resistance and Sn-based solder thermal resistance, respectively. These three types of thermal resistance decrease in order. Effect of shell temperature on junction temperature and $R_{\text{thjc}}$ is then discussed. As shell temperature increases, temperature variation of PN junction before and after heating and corresponding thermal resistance $R_{\text{thjc}}$ both increase.

Keywords. Junction temperature, thermal resistance, power diode, metal shell.

1. Introduction
Power diode has excellent electronic properties and has been widely used in aerospace applications. However, as it has high power density during accelerating aging test and actual using, its junction temperature may continue to increase. When its temperature rises to a certain extent, its heat transfer efficiency may decrease dramatically. In this way, failure may occur inside due to high thermal stress [1-4]. This failure can be avoided greatly by monitoring junction temperature accurately. However, junction temperature of diode cannot be measured directly in aging test. It should be calculated indirectly with its thermal resistance.

Infrared thermal map is a traditional method to test thermal resistance of diode [5]. However, as packaging cover may block transmission of infrared light in this method, diode should be opened to make chip exposed before testing. This process is difficult to realize during aging test. The electrical thermal resistance testing is an alternative method, because it can indirectly calculate junction temperature by measuring temperature sensitive parameters (TSP) of diode [6]. In earlier electrical method, Phase11 equipment was mainly adopted to measure thermal resistance. In this method, each TSP should be measured after junction temperature reached thermal equilibrium state. In addition, diode should be heated and cooled for several times to obtain TSP at different temperatures. It made testing time too long and limited its application field. Joint Electron Device Engineering Council (JEDEC) then proposed transient dual interface (TDI) method. In TDI method, TSP at different temperatures can be measured only by heating and cooling diode once, greatly reducing testing time. In this way, junction-to-case thermal resistance ($R_{\text{thjc}}$) can be obtained within a shorter time, greatly improving testing efficiency.

In this paper, TDI method was adopted to test thermal resistance of XX diode using T3ster equipment. Combined with internal structure analysis, heat transfer path inside this diode was
effectively analyzed. The thermal resistance of each structure inside this diode was then analyzed through structure functions. The influence of each structure on overall thermal resistance was identified. At last, effect of shell temperature on $R_{thjc}$ and junction temperature was discussed.

2. Transient Dual Interface Method Based on T3ster Equipment
The internal structure and packaging materials of XX diode may significantly affect its heat transfer efficiency. Figure 1 shows images of external and internal visual inspection of XX diode. The diode adopts metal packaging: the metal shell is mainly made of kover alloy, and its external and internal surfaces are both coated with Au layers. The diode contains two PN junctions. The top side of first PN junction is connected to pin 1 with two aluminum wires. Its bottom side is bonded to substrate with Sn-based metallic alloys. The second PN junction is connected to pin 3 with two aluminum wires and bonded to substrate with Sn-based metallic alloys, respectively. Therefore, the first and second PN junctions are parallel connected. The substrate is connected to pin 2 as grounding end.

![Figure 1. Images of external and internal visual inspection for XX diode: (a) External top view; (b) External bottom view; (c) Internal view.](image)

The principle of electrical thermal resistance testing is to calculate junction temperature by testing temperature sensitive electrical parameters. The positive voltage drop of PN junction in diode is correlated with temperature. It is not only easy to measure, but also linearly varies in a certain temperature range. Therefore, voltage drop of PN junction was selected as temperature sensitive parameters of diode in this paper. Before testing voltage drop of PN junction, it was necessary to determine K coefficient ratio of voltage drop and temperature. The specific process was as follows: firstly put diode inside oil tank without powering it; then increase oil temperature to heat diode; finally measure temperature sensitive parameters as its junction temperature increased.

After obtaining K coefficient curves of diode, transient thermal resistance curves can be tested. Before starting test, diode was connected according to testing circuit of transient thermal resistance shown in figure 2. The process can be divided into heating and testing stage: during heating stage, diode was powered by heating current $I_H$ to raise its temperature; during testing stage, heating current $I_H$ was shut down and replaced by testing current $I_M$ to measure voltage drop of PN junction. Voltage drop of PN junction was tested by sensor $V_F$ on the T3ster equipment. The current direction of $I_H$ and $I_M$ was consistent. Therefore, $V_F$, $I_H$ and $I_M$ all showed positive values (+).
The diode was fixed on Cu cold plate by pressure valve. The valve pressure was adjusted to 0.1MPa. If valve pressure was insufficient or too high, the contact area between diode shell and Cu cold plate may be changed. Then heat transfer path (firstly from chip to shell, then to Cu cold plate) may be influenced, affecting accurate measurement of thermal resistance curves. The temperature of Cu cold plate remained at 25°C. Due to direct contact between metal shell and Cu cold plate, shell temperature of diode was consistent with that of Cu cold plate.

After diode was connected into circuit and fixed on Cu plate, heating current IH was applied to diode in order to change its voltage drop. When its voltage drop remained stable, temperature of PN junction reached thermal steady state. At this time, IH was shut down and switched to testing current IM. According to product manual of this diode, IH was set to 28A, and IM was set to 5mA. During testing stage, voltage drop of this diode was recorded by T3ster software. The obtained data was processed to generate transient temperature curves and corresponding thermal resistance curves.

Thermal resistance curves were measured twice in transient dual interface method for the same diode. For the first test, metal shell of diode directly contacted with Cu plate to make their interface dry. For the second test, a thin layer of thermal grease was coated between them to make their interface wet. For the first test, as the contact area between metal shell and Cu cold plate was rough, there was air with poor thermal conductivity at the interface. It may increase the contact thermal resistance significantly. Therefore, shell surface of diode can then be identified with the above measurements. In order to determine the separating point more accurately, the primary two thermal resistance curves were then transformed into structure functions. The accurate thermal resistance $R_{thjc}$ can then be obtained by separating point of structure functions.

### 3. Analysis of Thermal Resistance Results in Transient Dual Interface Method

PN junction of power diode may generate a large amount of heat during using. According to internal structure shown in figure 1, it is slow for diode to pass heat through thermal radiation or air flow to atmosphere. It is easier to transmit heat as the following path:

1. Firstly conduct heat from chip to Sn-based metallic alloys.
2. Secondly conduct from Sn-based alloys to Au-coated metal shell.
3. Then conduct from metal shell to thermal grease.
4. Finally conduct from grease to Cu cold plate.

If there is no grease, heat is directly conducted from metal shell to Cu cold plate.

Figure 3 and figure 4 show structure functions and its local image of diode in transient dual interface method, respectively. The differential and cumulative structure functions are both separated at the position where thermal resistance $R_{th}$ is larger than 1 K/W.
According to thermal standard JESD51-14 [7], when $R_{thjc}$ is above 1K/W, the separation point of transient $Z_{th}$ curves cannot directly evaluate thermal resistance junction-to-case $R_{thjc}$. It is more accurate to determine $R_{thjc}$ from the separation point of structure functions. Structure functions contain differential and cumulative structure functions. Noise in $Z_{th}$ curves may generate inevitable numerical disturbances of structure functions. It may be further enhanced in differential structure functions. Therefore, cumulative structure functions are more recommended to evaluate thermal resistance $R_{thjc}$ instead of differential structure functions. As shown in figure 4, $R_{th}$ corresponding to the separation point of cumulative structure functions is approximately 1.23K/W. Therefore, thermal resistance $R_{thjc}$ of this diode is about 1.23K/W.

Figure 3. Structure functions of diode in transient dual interface method.

Figure 4. Local image of structure functions of diode in transient dual interface method.
The thermal resistance of each structure inside diode can be obtained according to the distance between each main peak on the differential structure functions. According to internal structure and heat transfer path, thermal resistance $R_{th}$ of this diode is mainly made up of three structures, namely PN junction thermal resistance, Sn-based solder thermal resistance and metal shell thermal resistance. On the differential structure functions, the horizontal scale $R_{th}$ from original point to the first main peak represents thermal resistance of PN junction (about 0.72K/W). The $R_{th}$ from the first to second main peak represents thermal resistance of Sn-based solders (about 0.15K/W). The $R_{th}$ from the second main peak on differential structure functions to $R_{thjc}$ (1.23K/W) represents thermal resistance of metal shell (about 0.36K/W). There are some small oscillation peaks between second main peak and $R_{thjc}$ (1.23K/W) in the differential structure functions. This phenomenon may be caused by interfacial thermal resistance between Au coating and kover alloy in metal shell. However, it does not occur in cumulative structure functions. The thermal resistance of PN junction is larger than that of Sn-based solders and metal shell. As there are two PN junctions inside the packaging structure, the chip produces more heat and makes its thermal resistance higher. The thermal resistance $R_{thjc}$ (1.23K/W) is equal to the sum of PN junction thermal resistance (0.72K/W), Sn-based solder thermal resistance (0.15K/W) and metal shell thermal resistance (0.36K/W). The critical point of cumulative structure functions is boundary point of each structure inside the diode. The horizontal scale $R_{th}$ corresponding to the first main peak on differential curves is very close to the first turning point of cumulative functions. The $R_{th}$ corresponding to the second main peak is also very close to the second turning point of cumulative functions. It further verifies the accuracy of structure functions in analyzing thermal resistance of each structure. In addition, cumulative function with small slope is relatively flat. It indicates that this region has lower thermal conductivity or smaller cross-sectional area, resulting in larger thermal resistance: PN junction (about 0.72K/W) > metal shell (about 0.36K/W) > Sn-based solder material (about 0.15K/W). The slope of cumulative structure functions also decreases in order: PN junction section is the most flat; metal shell section is relatively steep; Sn-based solder section is the steepest. Their thermal resistance decreases in turn: heat transfer efficiency of PN junction is worse, while that of Sn-based solders or metal shell is better.

4. Effect of Shell Temperature on $R_{thjc}$ and Junction Temperature

In this experiment, heating and testing current was set to 28A and 5mA, respectively. Power produced by diode was 34.5W. The shell temperatures of diode were kept at 25, 40, 50, 60 and 70℃, respectively, by adjusting Cu cold plate temperature. As shell temperature increased, corresponding thermal resistance $R_{thjc}$ was 1.23, 1.24, 1.25, 1.30, 1.32K/W, respectively. And temperature variation of PN junction before and after heating also showed a rising trend. The temperature variations were 42.44, 42.78, 43.13, 44.85 and 45.54℃, respectively. This phenomenon can be explained by heat transfer principle, as shown in equation (1) [8]:

$$Q = h \cdot A \cdot \Delta T$$  \hspace{1cm} (1)

In equation (1), $Q$ is heat transfer quantity. $h$ is heat transfer coefficient. $A$ is heat transfer area. $\Delta T$ is the average temperature difference between hot and cold medium. The equation (1) shows that heat transfer quantity is mainly determined by three factors: average temperature difference $\Delta T$, heat transfer coefficient $h$ and area $A$. When heat transfer coefficient $h$ and area $A$ are fixed, heat transfer quantity $Q$ is mainly determined by average temperature difference $\Delta T$. The heat transfer quantity $Q$ has a linear relationship with average temperature difference $\Delta T$. If heat transfer quantity $Q$ increases, temperature difference $\Delta T$ also rises.

During transient thermal resistance testing, temperature of PN junction is close to that of metal shell before heating. As diode is driven by heating current, temperature of PN junction increases. However, shell temperature is constant during this process. Therefore, initial temperature of PN junction is still close to that of metal shell after heating. The temperature variation of PN junction ($\Delta T_{0}$) before and after heating is approximately equal to temperature difference $\Delta T$ between PN junction and metal shell after heating. When shell temperature is low, heat from PN junction can be quickly and
easily transmitted to metal shell and Cu cold plate. The corresponding heat transfer quantity \( Q \) from PN junction to metal shell is smaller. According to equation (1), temperature difference \( \Delta T \) between PN junction and metal shell is smaller. Therefore, temperature variation of PN junction \( (\Delta T_0) \) before and after heating is smaller. When shell temperature is set higher, heat begins transferring from metal case to PN junction before driving the diode. Temperature of each structure inside diode all increases. Heat accumulates along the heat transfer path. After driving the diode with heating current, temperatures of each structure (including PN junction) further increase. When heat transfer system reaches dynamic thermal equilibrium state, temperature of PN junction tends to be stable. However, it is more difficult to transmit heat from PN junction to metal shell. It leads to higher heat transfer quantity \( Q \). In this way, corresponding temperature variation of PN junction \( \Delta T_0 \) increases. On the other hand, \( R_{thjc} \) is the ratio of temperature difference (between PN junction and metal shell) to power according to definition. Therefore, \( R_{thjc} \) is also the ratio of junction temperature variation \( \Delta T_0 \) to power. Therefore, when power is constant, if junction temperature variation \( \Delta T_0 \) increases, thermal resistance \( R_{thjc} \) also increases. The above analysis demonstrates that temperature variation of PN junction \( (\Delta T_0) \) before and after heating and corresponding thermal resistance \( R_{thjc} \) both increase with the rise of shell temperature.

5. Conclusion

Based on transient dual interface method, junction-to-case thermal resistance \( (R_{thjc}) \) of XX diode is measured by T3ster equipment in this paper. \( R_{thjc} \) of each structure inside diode is effectively analyzed with structure functions. When shell temperature is 25°C, thermal resistance \( R_{thjc} \) is about 1.23K/W. It is mainly made up of PN junction thermal resistance, metal shell thermal resistance and Sn-based solder thermal resistance. These three types of thermal resistance decrease in order. Effect of shell temperature on \( R_{thjc} \) is then discussed. With the increase of shell temperature, temperature variation of PN junction and corresponding thermal resistance \( R_{thjc} \) both increase. The above results can be critical parts of structure analysis and material design for power diode. They can provide data supports and suggestions for electronic packaging design, material processing method and aerospace application of diode.

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