Study on the Cauer Thermal Network Model of Press Pack IGBTs

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Abstract: Press Pack IGBTs (PP IGBTs) has been gradually applied in the high voltage and high current areas, for its high power density, double side cooling and high reliability. The cauer thermal network model of PP IGBTs is proposed based on the boundary effect according to heat spreading angle in this paper, and the difference between the IGBT and FRD chips is considered in this model. The thermal contact resistance among multi-layers within PP IGBTs, which is calculated and corrected by the experiment, is also included in this model. The finite element method (FEM) model is used to verify the accuracy of the cauer model, because the accurate measurement of the junction to case thermal resistance of PP IGBTs is extremely difficult. The thermal characteristic of PP IGBTs under different clamping force can be acquired through the cauer thermal model. It has significant influence on the thermal resistance optimization, as the thermal resistance percentage of the components in PP IGBTs can be obtained from the cauer thermal model.

1. Introduction
PP IGBTs has gradually been applied to high voltage and high power density applications, such as electric locomotives and HVDC transmission, for its high reliability, double side cooling, high power density and easiness to series [1], compared to typically wire bonded IGBT modules. The simplified internal structure of the studied PP IGBT is shown in Fig. 1, as it may be observed that the PP IGBT has a multi-layered structure. Two copper electrodes (collector and emitter pole) provide the electrical and thermal paths for the silicon chips, and the silicon IGBT chips are surrounded by two molybdenum plates which help with the uniform distribution of the clamping force. A silver shim plate, together with a silicon IGBT chip and two molybdenum plates, is to form a chip assembly. External clamping force is needed to keep all components within PP IGBTs both electrical and thermal contact well. Thermal is the most popular issue of the power semiconductor devices, Temperature distribution and the maximum junction temperature within power devices are the key parameters to restrict the improvement of power density.
The press pack packaging technology has been only used for very high power devices like injection enhanced gate transistors (IEGTs), gate turn off thyristors (GTOs), integrated gate commutated thyristors (IGCTs) and diodes. Since the experience with press pack packaging of those high power devices, the packaging concept has also been applied to IGBTs more recently. Temperature distribution and reliability researches on PP IGBTs found in the literature are briefly summarized as follows. T.Poller. et al. discussed the temperature distribution and pressure distribution within PP IGBT under power cycling phase in 2012 [2], through finite element method simulations. A. C.Busca et al. proposed a thermal model of pure IGBT chips in the PP IGBT to discuss about the transient thermal impedance [3]. D.Ze Chun et al. analyzed the junction to case thermal resistance of PP IGBTs through the theooretical and FEM model, and compared with the experiment results in 2013[4].

In this paper, a cauer thermal network model of PP IGBTs is proposed based on the boundary effect according to heat spreading angle, and the difference between the IGBT and FRD chips is considered in this model. The thermal contact resistance among multi-layers within PP IGBTs is also contained in the model in order to couple with the influence of the clamping force. Accurate measurement of the junction to case thermal resistance of PP IGBTs is extremely difficult, for a clamping force of about 1.2kN/cm² is needed to keep the PP IGBTs working well. The thermocouples located between the case and heatsink, which is required for the measurement of the junction to case thermal resistance, will be damaged under such high clamping force. The junction to heatsink thermal resistance of PP IGBTs was given in the datasheet of WESTCODE, rather than the junction to case thermal resistance. Hence, the FEM model is proposed to verify the accurate of the cauer thermal model. The structure of this paper is as follows. Internal structure and literatures' review of PP IGBTs are presented in the introduction. The determination of the thermal resistance and thermal capacity, including thermal contact resistance, is introduced in the cauer thermal model section. The theory of the bounding effect according to the heat spreading angle and the determination of the spreading anlge in PP IGBTs also are elaborated in detail in the second section. A case of 3300V200A PP IGBT is studied in the third part. The accuracy of the cauer thermal network model of the 3300V200A PP IGBT is verified by FEM model in the fourth segment. Conclusions and outlook are rasied in the last part.

2.CAUER THERMAL MODEL

The thermal behavior of power semiconductor devices can be predicted using foster and cauer thermal model. The foster model is commonly used and its parameters can be easily obtained by fitting the model to a thermal impedance curve. But foster models can’t be splited or merged and the node in a foster model have no real physical meaning. The other famous thermal model is cauer model, its parameters can be obtained either by calculations based on geometric parameters and thermal properities or by fitting the model to a thermal impedance curve. The nodes in a cauer model have physical meaning and therefore allow access to the temperatures of the internal layers. The foster model and cauer model can be converted to each other through the time domain transformation. The cauer thermal model is selected for the PP IGBTs in order to elaborate the internal structure more accurate. The dynamic cauer thermal model of PP IGBTs is shown in Fig. 2.
PP IGBTs is composed of IGBT chips and FRD chips, and every chip has its own heat transfer path, as shown in Fig. 1 the red frame is simplified diagram of the heat transfer path of the IGBT chip. The parameters in the blue frame shown in Fig. 2 are the thermal resistance and thermal capacity of the components of PP IGBT.

A. Parameters in Single Chip Path

The thermal resistance and thermal capacity of the single chip heat path can be obtained by the geometric parameters and thermal properties of the components, as shown in (1)-(3).

\[
R_{th} = \frac{d}{kA} \quad (1) \\
C_{th} = c_{heat} \cdot \rho \cdot d \cdot A \quad (2) \\
\tau = R_{th} \cdot C_{th} \quad (3)
\]

Where \( R_{th} \) denotes the thermal resistance [K/kW], \( C_{th} \) is the thermal capacity [J/K], \( \tau \) represents the time constant, \( d \) represents the thickness [m], \( k \) represents the thermal conductivity [W/(m*K)], \( A \) is the cross sectional area [m^2], \( c_{heat} \) is the constant pressure specific heat [J/(kg*K)] and \( \rho \) is the material density [kg/m^3].

The thermal contact resistance among multi-layers within PP IGBTs is mainly influenced by the clamping force and temperature. It must be considered in the thermal model to make it more accurate. The interface specific thermal contact resistance can be determined experimentally by measuring the temperature drop across the contact interface. Another possibility is to use a theoretical or semi-empirical model to calculate the thermal contact resistance. In this paper, a single IGBT and FRD chip submodule are made in order to explain the thermal contact resistance between layers more explicitly. The single IGBT chip submodule structure diagram and test bench are shown in Fig. 3. The thermal contact resistance among multi-layers is analyzed using the semi-empirical model proposed by Bahrami at al. [5], and corrected by the experiment result, as shown in Fig. 4.
B. Boundary Effect

Constriction and spreading resistances exist whenever heat flows from one region to another of different cross sectional area. The term constriction is used to describe the situation where heat flows into a narrower region, and the spreading is used to describe the case where heat flows out of a narrow region into a larger cross sectional area. The boundary effect must be considered in the calculation of the thermal resistance and thermal of the collector and emitter. As shown in Fig. 5, the collector side Molybdenum and pedestal are regard as the heat source, the collector and emitter are regarded as the heat dissipation baseplate.

Fig. 5 Thermal lateral heat spreading effect in materials

Where \( r \) is the radius of circular heat sources, \( l \) is the baseplate thickness, \( \beta \) represents the spreading angle (\( 0<\beta<90^\circ \)). The calculation of the spreading thermal resistance is determined by the formula (4).

\[
R = \frac{1}{k} \int_0^r \int A dA = \frac{1}{k} \int_0^1 \pi (r + x \tan \beta)^2 dx
= \frac{1}{k} \frac{1}{\pi r^3} l - \frac{1}{k} \frac{1}{\pi r^3} M
\]

(4)

Where \( M \) is the coefficient of the spreading thermal resistance, \( r \) is the radius of circular heat sources, and \( r = \sqrt{A/\pi} \) is used to calculate the radius of rectangular heat sources. The spreading thermal capacity is determined by the formula (5) based on the spreading thermal resistance formula.

\[
C = c \rho \int_0^r A dx = c \rho \int_0^1 \pi (r + x \tan \beta)^2 dx
= c \rho \frac{(r + l \tan \beta)^3 - r^3}{3 \tan \beta}
\]

(5)

The geometric parameters of the baseplate can be considered as two cases, as shown in Fig. 6, in order to approximate the realistic situation. The spreading thermal resistance and thermal capacity are calculated by the formula (6) and (7).
\[
(a) \quad R \geq L \quad \quad (b) \quad R < L
\]

Fig. 6 Two spreading case

\[
R = \frac{1}{k \pi r} \left( \frac{l}{r + \tan \beta} \right) + \frac{r(l-h)}{R^2} = \frac{1}{k \pi r} M \tag{6}
\]

\[
C = c \rho \pi \left( r + l \tan \beta \right)^3 - r^3 \quad \quad \text{with} \quad \rho \pi R^2 (l-h)
\]

\[
= \frac{c \rho \pi R^2 (l-h)}{3 \tan \beta \cdot \left( r + l \tan \beta \right)^3 - r^3} \tag{7}
\]

The equivalent thickness \( h \) is determined by the formula (8), and the spreading thermal resistance and capacity can be calculated after the equivalent thickness is given.

\[
h = \min \left( \frac{R - r}{\tan \beta} , l \right) \tag{8}
\]

**C. Determination of the Spreading Angle**

45° is commonly used to calculate the situations as small heat sources and quick estimation (the accuracy ranges from 5%-20%), but is not suitable for multi-layers and large heat sources any more [6]. A value of 26.6° is also used for the overall fit in many literatures, but the accuracy is not enough for the long heat dissipation path. The spreading angle determination of the PP IGBT is proposed in this paper.

The baseplate equivalent radius \( R \) is used as a baseline to normalize dimensions, as shown in (9) and (10).

\[
r_s = \frac{r_s}{R}, \quad 0 \leq r_s \leq 1 \tag{9}
\]

\[
l_i = \frac{l_i}{R}, \quad 0 \leq l_i \leq \infty \tag{10}
\]

The heat source relative size and baseplate relative thickness are taken into consideration in the determination of the spreading angle. The calculation is \( \tan \beta = k_1 \cdot k_2 \), where \( k_1 \) and \( k_2 \) are the coefficient of the heat source relative size and baseplate relative thickness respectively. For \( r_s \leq 1 \), namely the heat source is much smaller than the baseplate, the spreading angle is supposed to 45° (\( k_1 =1 \)). For \( r_s = 1 \), namely the heat source is equal to the baseplate, and the coefficient of \( k_1 \) is equal to zero. The coefficient of the heat source relative size \( k_1 \) is approximate to (11) with the first-order linear fitting.

\[
k_i = 1 - r_i \tag{11}
\]

For the situation that the value of \( \frac{l_i}{r_s} \) is relative high, the spreading angle is assumed to 45°. The thermal lateral heat spreading effect is not considered for the value of \( \frac{l_i}{r_s} \) is relative low, namely the heat source is closed to the bottom of the baseplate.

\[
k_2 = \frac{l_i}{(l_i + k \cdot r_s)} \tag{12}
\]

Where \( k \) is the coefficient ranges from 0 to 1. The value of 32.5° is good for \( \frac{l_i}{r_s} \leq 1 \), revealed in the literature R.F.David [7].

The spreading angle of the PP IGBT is shown in (13), which is coupled with the influence of the heat source relative size and baseplate relative thickness.
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\[
\tan \beta = k_1 \cdot k_2 = \frac{l_n}{l_n + 0.57 r_n} (1 - r_n) \quad (13)
\]

3. CASE STUDY
The internal structure and chip numbers of the studied PP IGBT of 3300V200A are shown in Fig. 2. Groves are shaped into the pedestals on the emitter side for the gate pin of the housing. The silver plates are not considered in the FEM model in this paper, as they are very thin in comparison with the other components. The geometric parameters of the studied PP IGBT are shown in Tab. 1.

![Fig.7 Top view of the studied PP IGBT](image)

| Component   | Surface area[mm²] | Thickness[mm] |
|-------------|-------------------|---------------|
|             | IGBT  | FRD  | IGBT  | FRD  |
| Si          | 183.87 | 183.87 | 0.41  | 0.41 |
| Collector side Mo | 183.87 | 183.87 | 1.72  | 1.72 |
| Emitter side Mo | 86.03  | 88.28 | 1.2   | 1.2  |
| Pedestal    | 82.84  | 88.36 | 8     | 8    |
| Collector   | 1725.3 | 1725.3| 7.8   | 7.8  |
| Emitter     | 1725.8 | 1725.8| 8     | 8    |

A. Thermal Parameters in Single Heat Path
The thermal parameters of the single IGBT and FRD chip heat path can be obtained by the thermal properties, geometric parameters and formulas (1) to (10), as shown in Tab. 2.

| Component | Thermal resistance[K/kW] | Thermal capacitance[J/K] | Time constant[ms] |
|-----------|--------------------------|--------------------------|-------------------|
|           | IGBT        | FRD        | IGBT        | FRD        | IGBT   | FRD   |
| Si        | 17.2        | 17.2       | 0.12        | 0.12       | 2.06   | 2.06  |
| Collector side Mo | 67.79     | 67.79      | 0.70        | 0.70       | 47.49  | 47.49 |
| Emitter side Mo | 101.11    | 98.5       | 0.23        | 0.25       | 23.26  | 24.65 |
| Pedestal  | 245.11      | 229.79     | 2.25        | 2.41       | 552.7  | 552.66|
| Collector | 68.00       | 68.00      | 8.31        | 8.31       | 563.5  | 563.52|
The thermal contact resistance among multi-layers in Tab.2 is calculated and corrected by experiment results under the rated clamping force of 1kN.

B. Thermal Parameters in Equivalent Heat Path

The thermal resistance is connected in parallel, and the thermal capacity is connected in series within PP IGBTs, because both the IGBT chips and FRD chips in PP IGBT are connected in parallel. The 4 IGBT chips’ heat paths can be equal to an IGBT chip equivalent heat path, as well as the FRD chips, with the assumption that the thermal parameters and clamping force among chips are uniform. The parameters of the PP IGBT for the equivalent heat path are shown in Fig. 3.

Tab. 3 Equivalent path thermal parameters (@6kN)

| Component       | Thermal resistance [K/kW] | Thermal capacitance [J/K] | Time constant [ms] |
|-----------------|---------------------------|---------------------------|--------------------|
| Si              | 4.30                      | 8.60                      | 0.48               |
| Collector side Mo | 16.95                    | 33.90                     | 2.80               |
| Emitter side Mo | 25.28                     | 49.25                     | 0.92               |
| Pedestal        | 61.28                     | 114.90                    | 9.00               |
| Collector       | 20.80                     | 43.44                     | 25.82              |
| Emitter         | 48.90                     | 78.03                     | 24.29              |
| \( R_{c} \) Collector Mo | 25.51                    | 51.18                     | -                  |
| \( R_{c} \) Chip Mo C | 58.60                     | 59.60                     | -                  |
| \( R_{c} \) Chip Mo E | 42.47                     | 60.53                     | -                  |
| \( R_{e} \) Emitter Mo | 39.54                     | 79.22                     | -                  |

The thermal contact resistance shown in Tab. 3 is calculated under the rated clamping force of 6kN.

C. Results Analysis

Various transient thermal impedance curves of the IGBT equivalent heat path are shown in Fig. 8 based on the cauer thermal network model. The influence of different cooling conditions and clamping forces on the transient thermal impedance is compared.
The transient impedance of emitter side cooling is much higher than the one of collector side cooling at steady-state under the clamping force of rated 6kN. This is because that the heat path of the emitter side is quite longer than the collector side, as pedestals exist in the emitter. The transient impedance of double side cooling is extremely low at the steady-state, compared to both the emitter side cooling and collector side cooling. The clamping force has a significant influence on the transient thermal impedance, as it influence the thermal contact resistance. Fig. 8 shows the transient impedance of double side cooling under three different clamping force (-20%, rated, +20%).

The thermal resistance proportion of the IGBT chip equivalent path under rated clamping force (@6kN), in order to optimize the thermal resistance of PP IGBTs, is shown in Fig. 9. The thermal resistance of the pedestal, accounts for about 19%, contributes a large proportion to the total thermal resistance, and can be decreased by reducing the height if possible. The largest is the total thermal contact resistance of four interfaces, accounts for about 44%. Thus, the junction temperature and reliability are largely affected by the thermal contact resistance, especially under different clamping conditions. The thermal resistance and junction temperature distribution within the studied PP IGBT under different clamping conditions are shown in Fig. 10. Different clamping conditions with the rated clamping force of 1000 N are assumed to discuss the junction temperature distribution. If the rated junction temperature is 100℃, the junction temperature of the chip with a clamping force deviation of -20% will increases 2.3℃.
4. FEM MODEL

A FEM model is used to verify the accuracy of the cauer thermal network model in this paper. In order to simplify the FEM thermal model without reducing accuracy, the frame, PCB, gate spring of the studied PP IGBT are omitted.

A. Temperature Distribution

The temperature distribution between IGBT chips and FRD chips are different because of the difference of the power dissipation. Fig. 11 shows the sectional view of the temperature distribution under rated clamping force (@6kN).

![Fig. 11 Sectional view of temperature distribution within PP IGBT (@6kN)](image)

As shown in Fig. 11, thermal lateral heat spreading effect is obvious in the PP IGBT, and thermal conduction is exactly three dimensions rather than one dimension.

B. Thermal Resistance

Thermal resistance of the IGBT and FRD equivalent path under double side cooling can be calculated by the formula $R=\Delta T/P$, and the results of FEM model are compared with different cauer models, as shown in Tab. 4.

![Tab. 4 Thermal resistance comparison of different models under double side cooling (@6kN)](image)

As revealed in Tab. 4, the spreading angle proposed in this paper is more accuracy than the commonly used 45°, as well as the cauer model without coupling the thermal lateral spreading effect. There exist a slight distinction between the FEM model and the cauer model proposed in this paper, because the cauer thermal model is assumed to one dimension thermal conduction, but the thermal conduction in the PP IGBT is three dimensions.
5. CONCLUSIONS
In this paper, the cauer thermal model of PP IGBTs, coupled with thermal contact resistance and thermal lateral spreading effect, is proposed. A FEM model is used to testify the accuracy of the cauer model, and the boundary effect is demonstrated by the temperature distribution within PP IGBT.

The thermal resistance distribution within PP IGBTs can be reflected by the cauer thermal model proposed in this paper. Both the emitter and pedestal thermal resistance are relatively large, accounting for about 16% and 19% respectively. Thermal contact resistance is an extremely important parameter to optimize the thermal behavior, because all the interfaces’ thermal contact resistance among multi-layers within PP IGBTs accounts for about 44%, which has a significant influence on the thermal characteristic. The cauer thermal model is deeply affected by the clamping force, on account of the thermal contact resistance is clamping force sensitive. The junction temperature distribution under different clamping force conditions and cooling conditions can be obtained through this model.

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