Study on the Method to Measure the Junction-to-Case Thermal Resistance of Press-Pack IGBTs

Erping Deng, Zhibin Zhao, Peng Zhang, Jinyuan Li, and Yongzhang Huang

***Abstract*—Accurate measurement of the junction-to-case thermal resistance of press-pack insulated gate bipolar transistors (PP IGBTs) is a great challenge due to their special packaging style and working conditions. The traditional thermocouple and transient dual interface methods have been successfully applied to measure the junction-to-case thermal resistance of wire-bonded IGBT modules. In this paper, a single fast-recovery diode (FRD) chip submodule is fabricated to determine the best method to measure the junction-to-case thermal resistance of PP IGBTs. Therefore, both the traditional thermocouple method and the transient dual interface method were used to measure the junction-to-case thermal resistance of the collector-side cooling with the emitter-side adiabatic. The transient dual interface method, which does not require locating a thermocouple to measure the case temperature, is ideal for the PP IGBTs measurement based on the experimental results and theoretical verification. Most importantly, both bulk thermal resistance of specific layers and thermal contact resistance between multilayers in PP IGBTs can be obtained by transforming the transient thermal-impedance curve.**

***Index Terms*—Junction-to-case thermal resistance, press-pack insulated gate bipolar transistors (PP IGBTs), traditional thermocouple method, transient dual interface method.**

I. Introduction

TO SATISFY the growing requirements of applications of insulated gate bipolar transistor (IGBT) devices, the capacity and reliability have become great challenges for IGBT devices. Press-pack IGBTs (PP IGBTs) have gradually been applied to high-voltage and high-power-density applications such as electric locomotives and high-voltage direct current (HVDC) transmission because of their high power density, double-side cooling, and easy to connect in series [1], [2] compared to typical wire-bonded IGBT modules. The simplified internal structure of the studied PP IGBT is shown in Fig. 1, which shows a multilayered structure [3]. Two copper electrodes (i.e., collector and emitter poles) provide the electrical and thermal paths for the silicon chips. The silicon IGBT chips are sandwiched by two molybdenum plates, which assist the uniform distribution of the clamping force. A silver shim plate, a silicon IGBT chip, and two molybdenum plates form a chip assembly [3]. An external clamping force is also required to maintain the electrical and thermal contact of all components within PP IGBTs. It is well known that the thermal resistance is the strongest focus of semiconductor devices and the criterion to evaluate the ability of heat dissipation. Furthermore, accurate measurement of the junction-to-case thermal resistance is notably important for manufactories to optimize the packaging internal structure and to take full advantages of the devices for users.

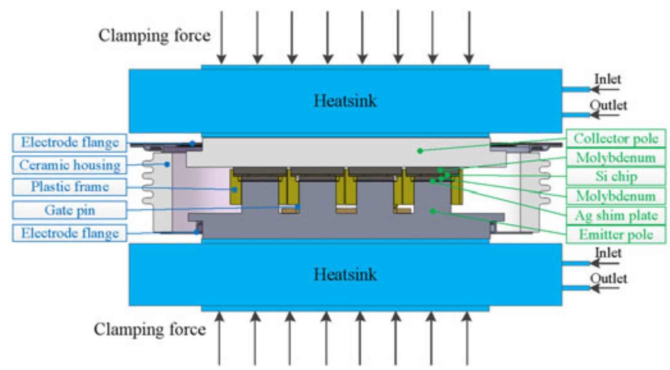

Fig. 1. Schematic diagram of PP IGBTs.

Currently, the most commonly used method to measure the thermal resistance of power semiconductors is the traditional thermocouple method, which was proposed by IEC, MIL standard [4] and JEDEC51-1 standard [5], and also called the *steady-state method*. The junction-to-case thermal resistance R_{jc} can be calculated using formula (1) because the junction temperature T_j, the case temperature T_c, and the power dissipation P of the device under test (DUT) are provided [6]

$$R_{jc} = \frac{T_j - T_c}{P}. \quad (1)$$

The junction temperature T_j can be indirectly measured using an electrical method. The relationship between the voltage drop caused by a notably small constant current and the junction

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temperature is the most used method, which is defined as the *K* factor [7]. Although this method is notably simple and easy to perform, the accuracy is significantly affected by the thermocouple position, clamping force for fixture, thermal grease, etc. Thus, this method is often not sufficiently reproducible and accurate [8]. In 2010, the JEDEC51-14 standard specified a new method (i.e., the transient dual interface method, which is also named as the *transient method*) to measure the junction-to-case thermal resistance R_{jc} of semiconductor devices without measuring the case temperature using a thermocouple between the case and the heatsink [9]. This method considerably improves the accuracy and reproducibility.

According to the measurement principle of the junction temperature T_j, the aforementioned two methods are the electrical method [10]. Additional, the optical and physically contacting methods are also introduced to measure the thermal resistance by some literatures, for example, the fiber optic and thermal camera methods [11]. However, those methods cannot be used in the packaged devices, let alone the devices that need the external clamping force.

The traditional thermocouple method is the most used method to measure the junction-to-case thermal resistance R_{jc} of wire-bonded IGBT modules, and the transient dual interface method was recently introduced by some semiconductor manufacturers, such as Infineon [12]. The difference of the packaging styles and working conditions between PP IGBTs and wire-bonded IGBT modules may make the methods well used in wire-bonded IGBT modules but not suitable for PP IGBTs. Furthermore, an external clamping force of approximately 1- 2 kN/ cm^2 is required to maintain the normal operation of PP IGBTs [13] which is much higher than the recommend clamping force of $10\,\mathrm{N/cm^2}$ for fixture during the thermal resistance measurement [9]. The thermocouple inserted between the case and the heatsink can be easily damaged due to the external clamping force, and the heat path will also be influenced by the inserted thermocouple. Unfortunately, the accurate measurement of the junction-to-case thermal resistance R_{jc} of PP IGBTs remains a great challenge. Instead of the junction-to-case thermal resistance R_{jc}, only the junction-to-heatsink thermal resistance R_{js} is provided in the datasheet of PP IGBT's manufacturers such as Westcode and Toshiba [14]. Z. C. Dou *et al*. measured the junction-to-case thermal resistance R_{jc} of PP IGBTs using the parallel and series connection relationship between the thermal resistance under the collector-side cooling and that under the emitter-side cooling [15]. The accuracy of the experimental results is still affected by the thermocouple position, thermal grease, etc.

In this paper, a single fast-recovery-diode (FRD) chip submodule is designed and fabricated to meet the requirements of the traditional thermocouple method for PP IGBTs, such as a specific channel for thermocouples to measure the case temperature was designed on the collector and emitter electrode pole surface. The FRD chip studied in this paper is 3300 V/100 A for power system application. The junction-to-case thermal resistance of the single FRD chip submodule was measured using both traditional thermocouple and transient dual interface methods. Most importantly, the effect of these two methods on PP IGBTs is discussed, and a comparison is made. Based on the experimental results, the most suitable method to measure the junction-to-case thermal resistance of PP IGBTs is proposed in this paper. The basic structure of this paper is set as follows. The basic principle of those two methods and the review of the junction-to-case thermal resistance measurement of PP IGBTs are introduced in the first part. The second section mainly presents the principle of the transient dual interface method and data analysis. A single FRD chip submodule is fabricated to measure the junction-to-case thermal resistance using those two methods in the experimental part. Then, the experimental results of the transient dual interface method are well verified by the theoretical values. Some conclusions are drawn based on the experimental data and analysis in the conclusion. Furthermore, a suitable method to measure the junction-to-case thermal resistance of PP IGBTs is introduced.

II. Measurement Principle

Between the two aforementioned methods, the traditional thermocouple method is relatively simple and the most common used method to measure the junction-to-case thermal resistance of power semiconductor devices. Therefore, the principle of the transient dual interface method is presented in this paper.

The transient dual interface method requires two measured transient thermal impedance (Z_{th}) curves of a power semiconductor device in contact with a temperature-controlled heatsink. The first test is performed with no thermal interface material between the DUT and the heatsink, i.e., direct contact or without grease. For the second measurement, a thin layer of thermal grease or oil is applied at the interface, i.e., contact with grease. The thermal grease in the interface changes the thermal contact resistance and ensures a clear separation of the Z_{th} curves. The transient thermal impedance that corresponds to the splitting point is defined as the junction-to-case thermal resistance R_{jc} [9].

A. Transient Thermal Impedance Curve

Fig. 2 shows the measurement principle of the Z_{th} curve [16]. Two direct current sources provide the heating and sensing currents for the device under test (DUT), respectively. A constant voltage V_{gate} is required to be applied to the IGBT chip's gate so the device channel is open and current flows through during the measurement. A heating current I_{drive} is flowed into the DUT to heat it to reach the thermal equilibrium. Then the heating current I_{drive} is switched to a sense current I_{sense} to measure the voltage drop during the cooling phase. The junction temperature T_j during the cooling phase is acquired through the recorded voltage drop and *K* factor, which is the relationship between voltage drop and junction temperature for short [16]. Finally, the transient thermal impedance $Z_{\mathrm{th,\ cooling}}(t)$ of the DUT during the cooling phase can be obtained by (2). Furthermore, the junction behavior of the heating phase is similar to the cooling phase, so the transient thermal impedance $Z_{\mathrm{th,\ heating}}(t)$ during

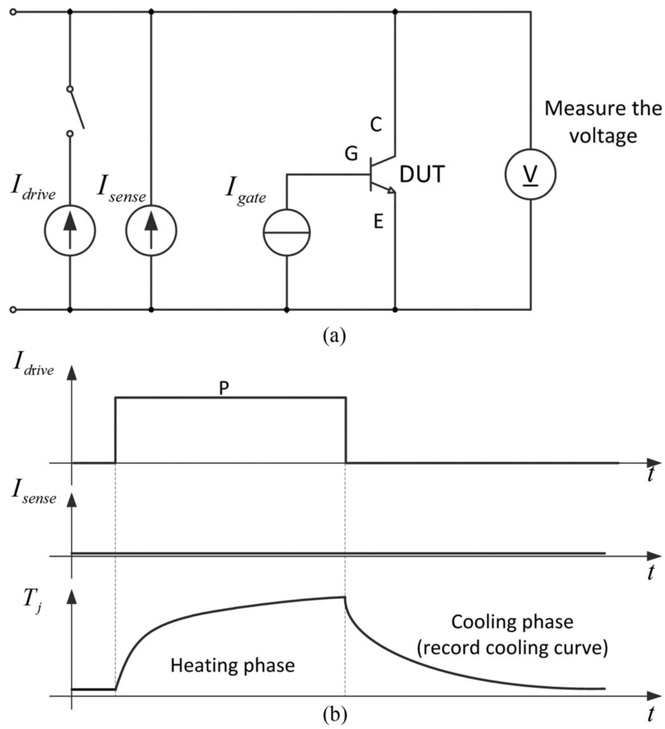


Fig. 2. Principle diagram of the measurement. (a) Test circuit. (b) Thermal transient test sequence.

the heating phase can be calculated by (3) [17]

$$Z_{\mathrm{th,cooling}}\left(t\right) = \left(T_j\left(t\right) - T_j\left(t=0\right)\right)/P \tag{2}$$

$$Z_{\mathrm{th,heating}}\left(t\right) = Z_{\mathrm{th,cooling}}\left(t=0\right) - Z_{\mathrm{th,cooling}}\left(t\right). \tag{3}$$

B. Determination of the Thermal Resistance

The principle of the determination of the junction-to-case thermal resistance of the power devices is shown in Fig. 3. Two Z_{th} curves are required to measure with two different contact interface conditions: with and without thermal grease, which causes the two Z_{th} curves to separate at some point of time t_s in Fig. 3(b). Because the heat paths only differ at the case surface, those two Z_{th} curves are always consistent from the junction-to-case surface. Therefore, the transient thermal impedance $Z_{\mathrm{th}}(t_s)$, which is specified at the splitting point, is assumed to be the junction-to-case thermal resistance R_{jc} of the DUT.

As defined in JESD51-14 [9], for power devices with thermally high conductive die attach, $Z_{\mathrm{th}}(t_s)$ is sufficiently close to the "steady-state resistance" to serve as a reliable measurement for R_{jc}. However, if the semiconductor package contains an internal barrier to the heat flow the two Z_{th} curves can diverge "too early", i.e., $Z_{\mathrm{th}}(t_s) < R_{jc}$ [18]. In this situation, these Z_{th} curves have to be converted to their corresponding structure functions in order to determine the junction-to-case thermal resistance [19]. In PP IGBTs, all the metal layers have a high thermal conductivity and the thermal contact resistance between layers is lower enough under such a high clamping

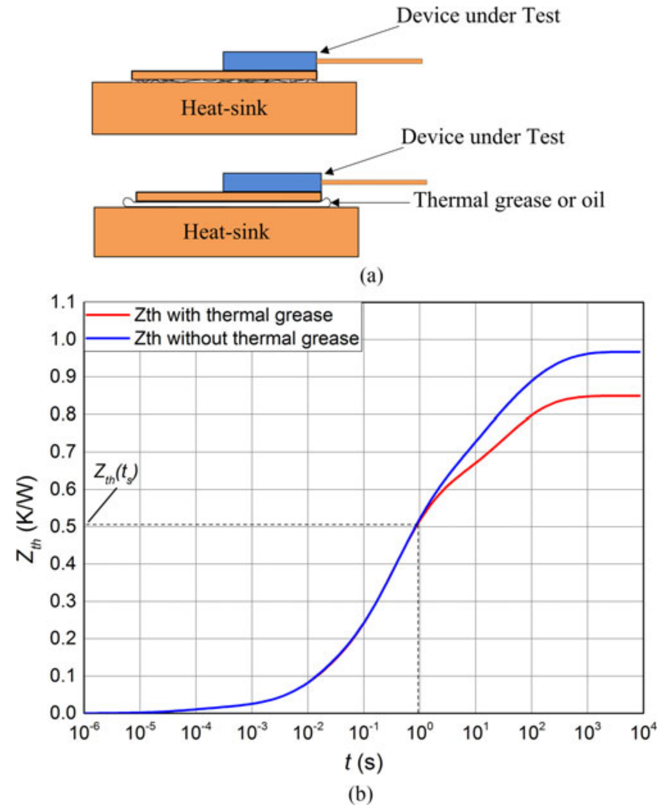


Fig. 3. Principle of the transient dual interface measurement. (a) Two different test conditions. (b) Transient thermal impedance curve.

force. Therefore, no internal barrier to the heat flow is expected in the press pack packaging and the separation of the Z_{th} curves is sufficiently closed to the "steady-state resistance." All the junction-to-case thermal resistance R_{th} in this paper is determined by the separation of the Z_{th} curves.

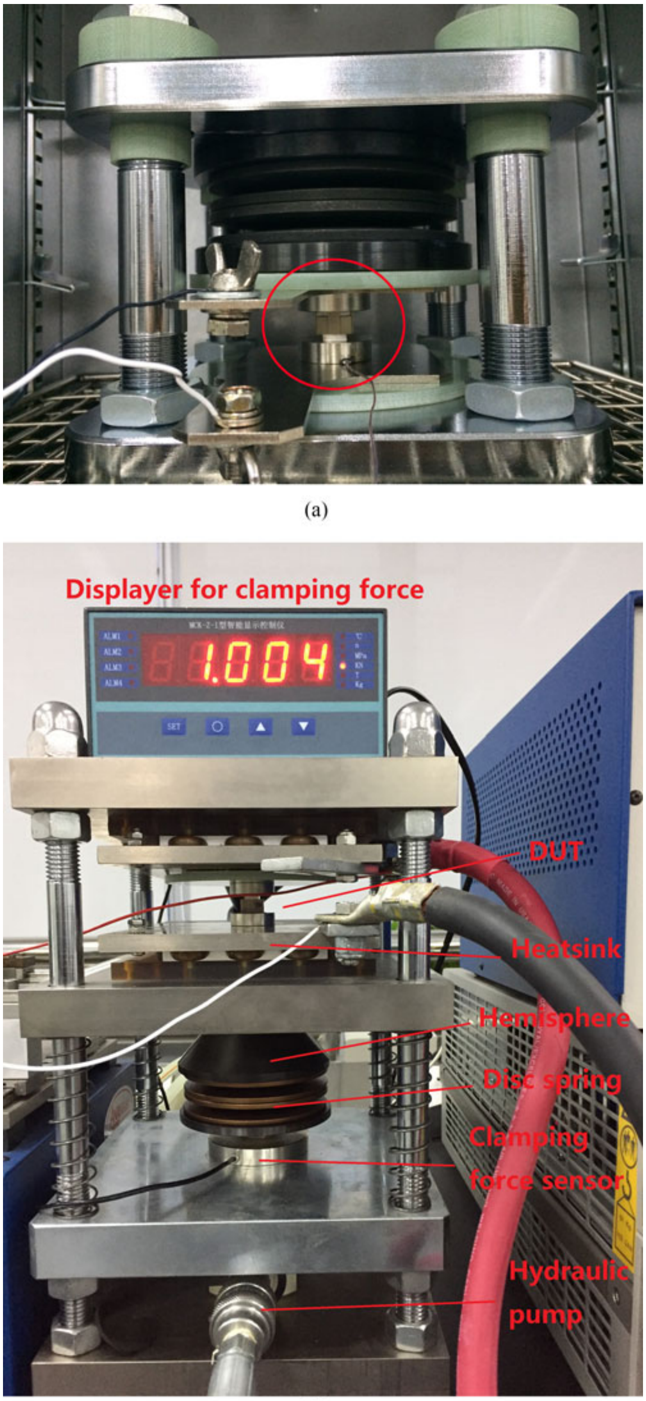
III. Experiments

A. Test Bench

The fixtures of the commercial thermal resistance tester are not suitable for PP IGBTs because of their special packaging style and working conditions. In this paper, we designed two fixtures dedicated for PP IGBTs and used the thermal resistance tester to measure the junction-to-case thermal resistance and transient thermal impedance curves, respectively.

According to the principle of the transient thermal impedance Z_{th} curve measurement, the K factor [7], which accounts for the relationship between the junction temperature and the voltage drop, should be measured to predict the junction temperature during the test. Then, the transient thermal impedance is recorded. The fixtures for the K factor and transient thermal impedance curve measurements are shown in Fig. 4.

Four nuts were used to constrain the displacement to sustain the desired clamping force, which was provided by a standard pressure machine. A disc spring was required to compensate for the physical movements during the clamping and thermal-expansion process. The clamping force hardly affected the K factor as long as the studied PP IGBT was in good contact



(a)

(b)

Fig. 4. Measurement fixtures. (a) *K* factor measurement fixture. (b) Thermal resistance measurement fixture.

because the measurement current was notably small [20]. Fig. 5 shows the results of the 3300 V/360 A PP IGBT manufactured by Westcode under 5 and 8 kN with a constant sense current of 20 mA. The results show that the fixture can fully satisfy the measurement requirements because the slopes (°C/V) are exactly identical, except for a difference of 0.02 (°C) in the intercept.

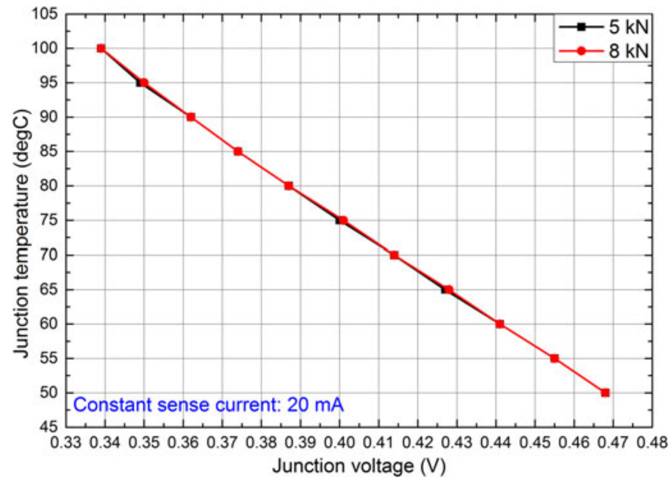


Fig. 5. Comparison between voltage-temperature calibration curves (*K* factor) measured with a clamping force of 5 and 8 kN.

The fixture to measure the transient thermal impedance curve consisted of dual heatsinks, a DUT, a disc spring, a clamping force sustaining plate, a hydraulic pump and a pressure sensor. Dual heatsinks are used to supply the needed clamping force and heat dissipation path. This fixture can easily realize the function of collector-/emitter-side and double-side cooling for the DUT via managing the dual heatsinks. The clamping force uniformity on the surface is also very important for the results. Thus, a hemisphere is proposed to in this fixture because it is very good at the surface flatness adjustment. As mentioned earlier, the disc spring is needed to compensate the physical movements during the process of clamping and thermal expansion. The clamping force sensor, which is connected in series with the DUT, is used to record the clamping force of the DUT and to deliver to display in real-time. The hydraulic pump provided a continuously adjustable clamping force ranges up to 50 kN, which fully satisfied the requirements of all current ratings of PP IGBTs.

B. Object of Experiment

As is known, multiple chips are connected in parallel in PP IGBTs to increase the current rating, so there is inevitably a slight difference among those chips. To exclude interference factors, a single FRD chip submodule was designed to predict the thermal resistance behaviour of PP IGBTs in this paper. The single FRD chip submodule is shown in Fig. 6, and the object in the test bench is marked in red in Fig. 4. The reason why we used a single FRD chip rather than a single IGBT chip submodule is to reduce the complexity of the experiment. Because an external constant voltage is required to apply to the IGBT chip's gate so the device channel is open and current flows through during the measurement. Meanwhile, grooves are needed to shape into the pedestals, as well as other components on the emitter side, for the gate pin of the housing.

Two copper electrodes (collector and emitter poles), an FRD chip, two molybdenum plates surrounding the FRD chip, and a silver shim plate form a single FRD chip submodule. The thermal resistance of the submodule under double-side cooling is

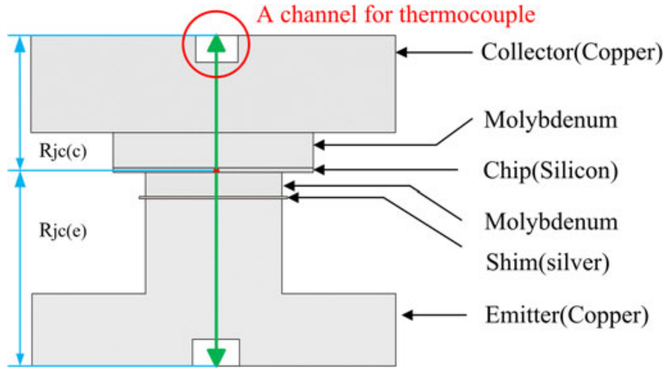


Fig. 6. Schematic diagram for the single FRD chip submodule.

the parallel relationship of the value under collector-side cooling ($R_{jc(c)}$) and emitter-side cooling ($R_{jc(e)}$). In this paper, the transient thermal impedance under collector-side cooling was measured with the emitter-side adiabatic.

According to the mounting instruction from the PP IGBTs manufactures such as ABB [21] and Westcode [22], a pressure of approximately $1.2\,\text{kN/cm}^2$ is ideal for PP IGBTs. Therefore, a clamping force of 1 kN was applied to the submodule according to its clamped area and the aforementioned standard pressure. This high clamping force on the submodule made the thermocouple, which was located at the interface between the case and heatsink to record the case temperature, malfunction. We designed both collector and emitter poles for the submodule in this paper, and a channel for thermocouples to measure the case temperature was designed on the pole surface to satisfy the requirements of the traditional thermocouple method. The thermocouple channel is marked in red in Fig. 6.

C. Experimental Results

1) Traditional Thermocouple Method: Many studies propose that the traditional thermocouple method is not sufficiently reproducible and accurate because the accuracy is affected by many factors such as the clamping force for fixture, thermal grease, thermocouple position, etc. Furthermore, much different from wire-bonded IGBT devices, the clamping force for the fixture also significantly affects the thermal contact resistance in PP IGBTs. In this paper, the junction-to-case thermal resistance of the single FRD chip submodule under different clamping forces was measured using the traditional thermocouple method and repeatedly tested under the rated clamping force (@ 1 kN).

a) Results of repetition measurement: The junction-to-case thermal resistance R_{jc} of the single FRD chip submodule with the collector-side cooling under rated clamping force (@ 1 kN) was repeatedly measured, and the results are shown in Table I. All experimental conditions were consistently maintained throughout the test, and the measurement number represents the repetition of the test. The disc spring can minimize the effect of thermal expansion to some extent. However, the submodule will sustain thermal expansion generated by the high temperature of the FRD chip with the external constraint by the fixture and eventually increase the clamping force because

TABLE I
RESULTS OF THE REPETITION MEASUREMENTS AT 1 kN

No	I_c (A)	P (W)	T_j (°C)	R_{jc} (K/W)	Deviation (%)
1#	50.082	121.3	125.4	0.73706	10.6%
2#	50.103	121.5	121.9	0.70084	12.4%
3#	49.998	121.3	118.1	0.66391	13.4%
4#	50.033	121.2	117.2	0.65580	14.0%
5#	50.096	121.6	116.0	0.64685	14.8%
6#	50.701	120.5	115.8	0.63617	15.4%
7#	50.075	121.7	115.7	0.63374	15.6%
8#	49.901	121.5	113.5	0.61666	15.6%
9#	49.963	122.0	112.8	0.61392	16.0%
10#	50.047	121.3	112.5	0.61280	17.8%
11#	49.914	122.1	112.0	0.60840	18.4%
12#	49.901	121.5	111.7	0.60052	18.6%

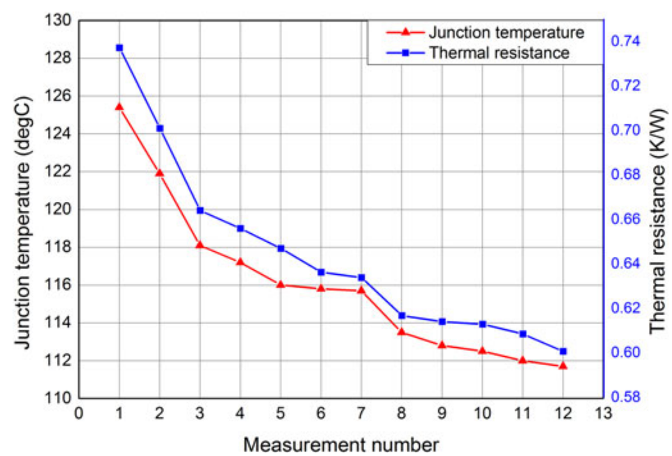


Fig. 7. Results of the repetition measurement at 1 kN.

that the disc spring is not able to totally eliminate the thermal expansion. The deviation in Table I is the increase in clamping force during the measurement and the base value for the deviation is the rated clamping force of 1 kN, which is applied to the submodule before the thermal resistance measurement. From the data in Table I, we observe that the thermal resistance R_{jc} is quickly reduced with the repeat measurement and tends to be approximately stable after the 12th test.

As shown in Fig. 7, the thermal resistance R_{jc} is reduced with the repeated measurement because the thermal contact resistance among multiple layers in the single FRD chip submodule is reduced. It can be proven that the change in thermal contact resistance with repeated test is caused by the high temperature during the measurement and external constraint. The temperature is the most important parameter that affects many material properties such as the microhardness. The high temperature decreases the microhardness of microcontacts (i.e., they soften). Thus, the microcontact of the contact surface experiences an elasticity deformation or even a plastic deformation at high temperature under the external clamping force during the measurement. Then, the decrease in microhardness leads to a larger contact surface area and reduces the thermal contact resistance. Although the temperature of the FRD chip and other components is reduced after the test is completed, the deformation remains unable to be fully restored to the previous state and

TABLE II
SURFACE ROUGHNESS COMPARISON

R_{a} (μm)	Collector_Mo	Collector_Chip	Emitter_Chip	Emitter_Mo	Emitter_Silver
Before	0.344	0.495	0.147	0.334	0.286
After	0.268	0.147	0.057	0.307	0.087

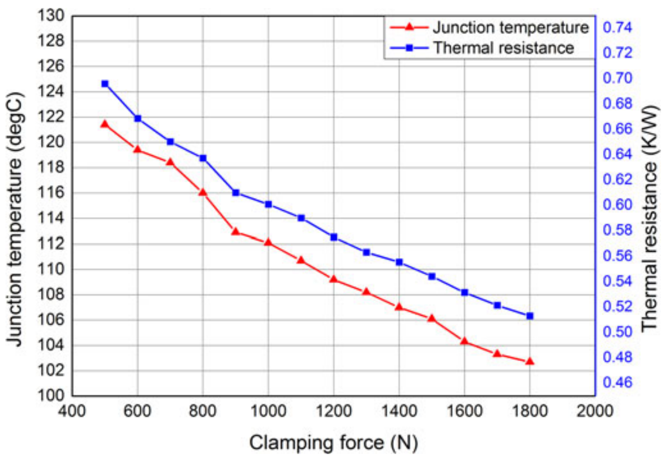


Fig. 8. Results under various clamping forces.

TABLE III
RESULTS UNDER VARIOUS CLAMPING FORCES

No	I_c (A)	P (W)	T_j (°C)	R_{jc} (K/W)	Deviation (%)
500	49.908	120.4	121.4	0.69583	15.88%
600	50.012	120.8	119.4	0.66828	11.29%
700	49.928	121.6	118.4	0.64991	8.23%
800	49.894	121.3	116.0	0.63698	6.08%
900	49.887	121.2	112.9	0.60960	1.52%
1000	49.914	121.2	112.1	0.60048	–
1100	49.949	121.3	110.7	0.58972	−1.79%
1200	49.942	121.3	109.2	0.57472	−4.29%
1300	50.061	122.1	108.2	0.56310	−6.23%
1400	49.949	121.8	107.0	0.55534	−7.52%
1500	49.998	122.4	106.1	0.54398	−9.41%
1600	49.935	122.4	104.3	0.53137	−11.51%
1700	49.963	122.7	103.3	0.52111	−13.22%
1800	50.103	123.1	102.7	0.51272	−14.61%

eventually causes a decrease of surface roughness. Surface properties, such as the surface roughness, no longer changes after several repeated thermal resistance measurements because the surface eventually undergoes a plastic deformation rather than elasticity deformation. The surface roughness of all contact surfaces in the single FRD submodule was measured after several repeated measurements through a surface roughness tester (Mitutoyo SURFTEST SJ-310), as shown in Table II and compared with the values before the thermal-resistance measurement.

R_a is the surface roughness; "before" and "after" denote the status of the thermal-resistance measurement.

As expected, the observed surface roughness of the components is much smaller after testing than before testing, particularly the components of the collector side, because the thermal-resistance test only measures the junction-to-case thermal resistance R_{jc} of the collector-side cooling with the emitter-side adiabatic.

b) Results under various clamping force: The material properties, machining precision and temperature and clamping force significantly affect the thermal-contact resistance. The aforementioned experimental results show that R_{jc} of the single FRD chip submodule is deeply affected by the temperature. Table III shows the experimental results under various clamping forces of the submodule (500−1800 N). The data show that the thermal resistance gradually decreases with the increase in clamping force, but the rate of decrease slightly declines. Similar to the effect of the temperature, the increase in clamping force decreases the microhardness and causes a larger contact surface area. Thus, the thermal resistance decreases with the increase in clamping force as shown in Fig. 8.

It is observed that the junction-to-case thermal resistance R_{jc} of the single FRD submodule under 1000 N is 0.60048 K/W, which is notably consistent with the value in Table I (0.60052 K/W). This phenomenon also indicates that the material property of microhardness no longer changes after the 12th test, and the thermal resistance tends to be stable.

2) Transient Dual Interface Method: According to the principle of the transient dual interface method, two Z_{th} curves should be measured with two different interface conditions between the DUT and the heatsink for the separation. The transient thermal impedance $Z_{\mathrm{th}}(t_s)$ at the splitting point is assumed to be the junction-to-case thermal resistance R_{jc} because the Z_{th} curve does not change from the junction to the case between those two cases. In general, the substrate is used for heat dissipation and electrical insulation between the semiconductor chips and the heatsink in typical wire-bonded IGBT modules or the packaging of TO-247. Thus, thermal grease (mostly electrical insulated) is the most commonly used interface material in contact interfaces to improve their thermal conductivity. Nevertheless, the packaging of PP IGBTs is completely different. Heatsinks are used to dissipate heat and conduct current in PP IGBTs. The electrical insulated thermal grease is no longer suitable for changing the interface conditions because it resists the flow of current. Furthermore, such a high external clamping force makes the thermal contact resistance between the DUT and heatsink notably small, which is notably difficult to distinguish the splitting point to determine the junction-to-case thermal resistance. To increase the difference of the interface between the DUT and the heatsink, a suitable metal thickness (such as a bus bar) is proposed to insert into the interface in this paper.

a) Results of repetition measurement: Similar to the traditional thermocouple method, the single FRD chip submodule cooling-phase curves of the collector-side cooling under the

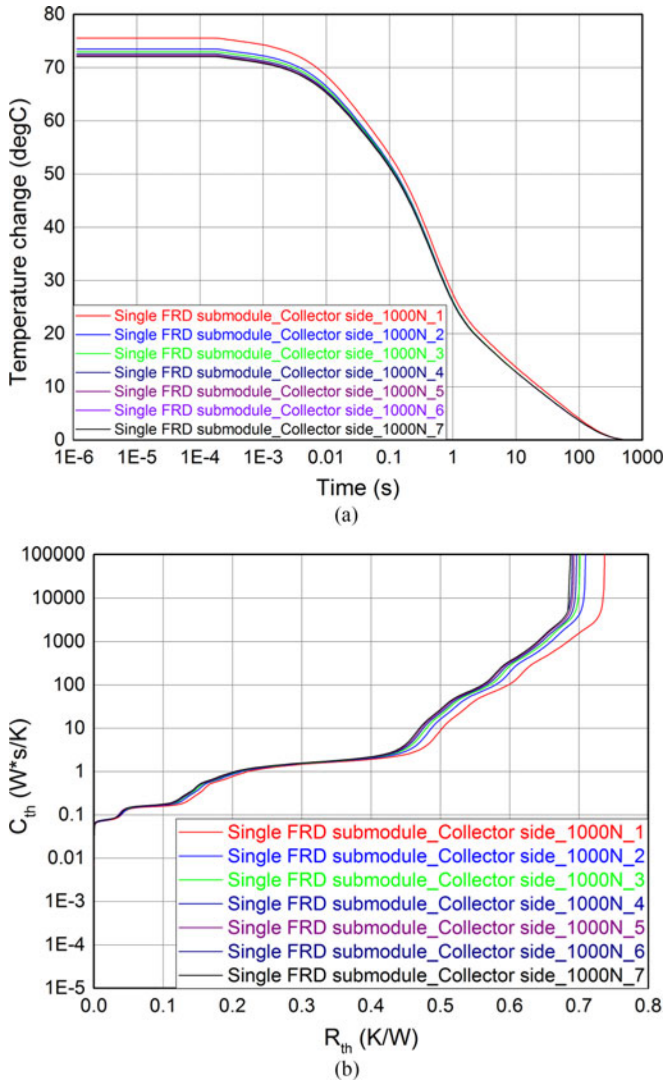


Fig. 9. Repeated measurements results at 1 kN. (a) Cooling-phase curves. (b) Cumulative structure functions.

rated clamping force of 1 kN are repeatedly measured. Fig. 9(a) shows the cooling-phase curves with seven repetition measurements. The data in Fig. 9(a) show that the junction temperature of the FRD chip gradually decreases with repeated tests, but the rate of decrease slightly declines, which is consistent with the results of the traditional thermocouple method. The cooling-phase curve can be transferred to the heating-phase curve and cumulative structure function to indicate the thermal contact resistance change more explicitly, as shown in Fig. 9(b). We can see that the thermal resistance, which is caused by thermal contact resistance, reduces with the repeated measurements.

b) Results under various clamping forces: The cumulative structure functions of the single FRD chip submodule under various clamping forces are also obtained through the measurement to show the influence of clamping force on thermal contact resistance, which is shown in Fig. 10. We can see that the cumulative structure function moves to the left as the clamping force increases, i.e., the thermal contact resistance is reduced. The thermal resistance on the left side of the red line, which is

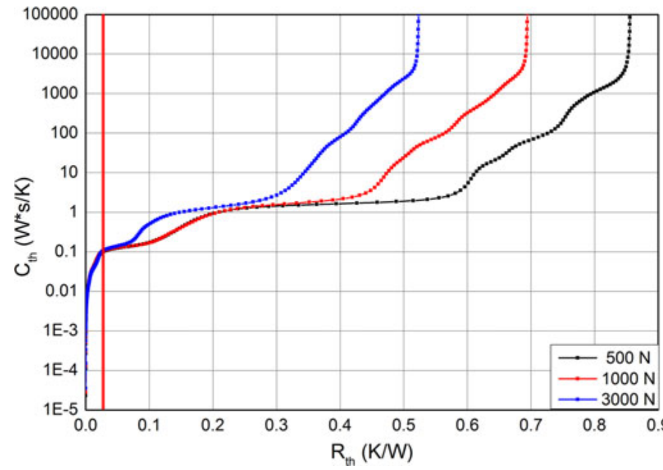


Fig. 10. Cumulative structure functions under various clamping forces.

consistent with various clamping force, is the FRD chip. Fig. 10 indicates the variation of the thermal contact resistance caused by various clamping forces more specify. Thus, not only the thermal contact resistance between the DUT and heatsink but also within the submodule will be affected by the clamping force.

According to the principle of the transient dual interface method, the $Z_{\rm th}$ curves from the junction to the case should not be changed between those two cases. In order to research the influence of the clamping force on the determination of the junction-to-case thermal resistance more specific, the transient thermal impedance curves under the clamping force of 0.8 and 1 kN with/without insert metal are measured. The results under the clamping force of 1 kN and slight change it to 0.8 kN with insert metal are shown in Fig. 11.

In Fig. 11(a), the $Z_{\rm th}$ curves are highly consistent before the splitting point with the exception of a slight discrepancy at 10^{-5} to 10^{-3}. The reason of the slight discrepancy is that the metal insertion slightly changes the thermal contact resistance between the FRD chip and the molybdenum plate when the test fixture and submodule were reassembled. The junction-to-case thermal resistance $Z_{\rm th}(t_s)$ of the single FRD submodule according to Fig. 11(a) is approximately 0.535 K/W based on the splitting point. In Fig. 11(b), we can see that the slightly change in clamping force during the measurement with insert metal change the thermal contact resistance within PP IGBT and eventually cause an earlier splitting point. The junction-to-case thermal resistance $Z_{\rm th}(t_s)$ according to Fig. 11(b) is difficult to identify and approximately 0.39 K/W, which is much lower than the normal value. The reason is that the clamping force variation with insert metal, which is changed from 1 to 0.8 kN by adjusting the hydraulic pump, changes the transient thermal impedance curve from the junction to the case and makes it different from the curve without insert metal. Thus, strictly keeping the clamping force in consistency during those two $Z_{\rm th}(t_s)$ curves measurement is extremely important for the transient dual interface method.

3) Results Analysis: According to the experimental results of the traditional thermocouple and transient dual interface

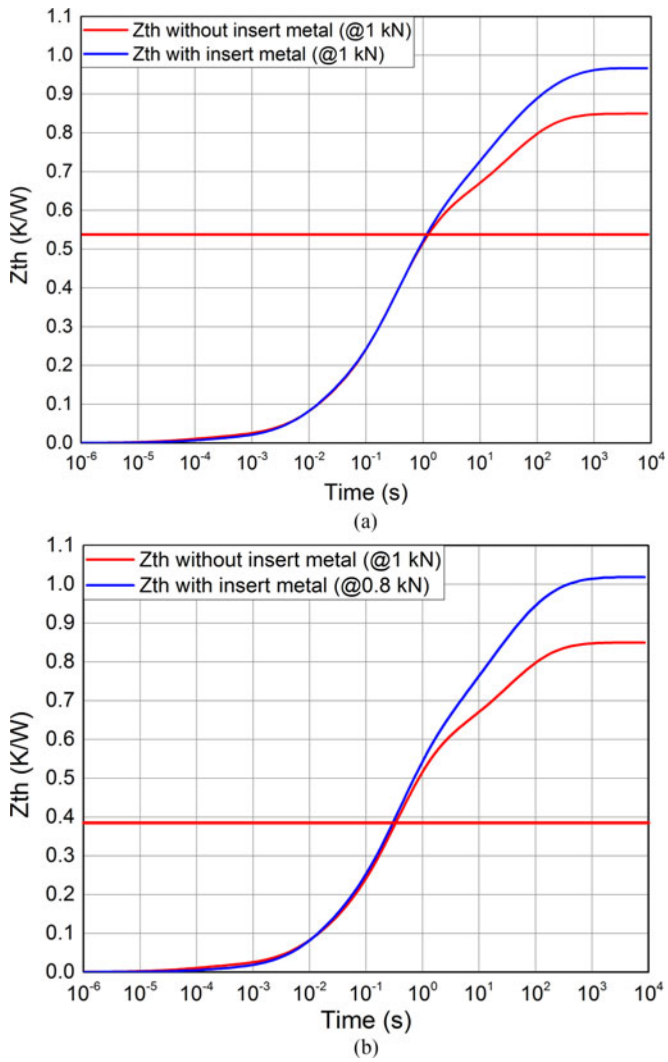


Fig. 11. Influence of the clamping force on the determination of the junction-to-case thermal resistance. (a) With a consistency clamping force (1 kN). (b) Slightly change in the clamping force.

methods, the thermal resistance of PP IGBTs is significantly affected by the temperature and clamping force because of the microhardness. The transient dual interface method obtained a slightly lower junction-to-case thermal resistance of the single FRD chip submodule (0.535 K/W) than the traditional thermocouple method (0.60048 K/W).

The experimental results of the traditional thermocouple and transient dual interface methods are slightly different. However, the $Z_{\mathrm{th}}(t_s)$ determined based on the splitting point of transient thermal-impedance curves is not necessarily equal to the "steady-state" junction-to-case thermal resistance R_{jc} defined by (1) and can be measured using the traditional thermocouple method. The reason is that the steady-state (long-term) heat flow distribution in the device differs from the transient heat flow distribution at time t_s [21]. The method that obtains a closer result to the actual thermal resistance remains to be verified.

The transient thermal-impedance curve describes the thermal-resistance change through the junction to the case during the heating/cooling phase and includes some important thermal information for each specific layer in the DUT. Cumulative and

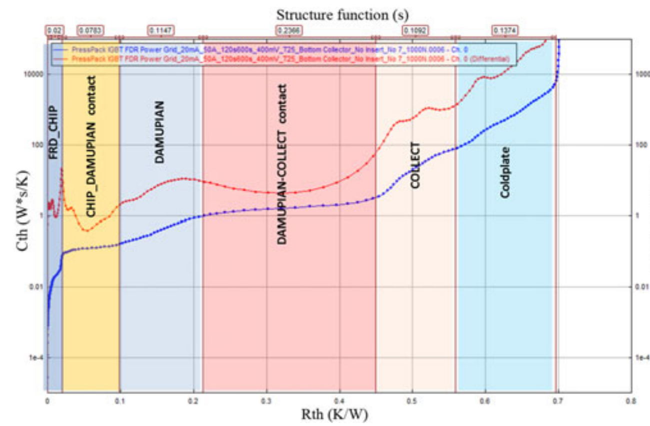


Fig. 12. Cumulative and differential structure functions.

differential structure functions can be derived from this curve through mathematical transformations such as deconvolution and discretization. The cumulative and differential structure function formulas are shown in (4) and (5), respectively

$$C(R) = c \cdot \rho \cdot k \cdot A^2 \cdot R \quad (4)$$

$$\rho(R) = dC(R)/dR = c \cdot \rho \cdot k \cdot A^2 \quad (5)$$

where $C(R)$ is the cumulative structure function and denotes the thermal capacity (W·s/K), $\rho(R)$ denotes the differential structure function $(\mathrm{W}^2 \cdot \mathrm{s/K}^2)$, R is the thermal resistance [K/W], A is the sectional area $[\mathrm{m}^2]$, k is the thermal conductivity $[\mathrm{W}/(\mathrm{m}\cdot\mathrm{K})]$, c is the constant-pressure specific heat $[\mathrm{J}(\mathrm{kg}\cdot\mathrm{K})]$, and ρ is the material density $(\mathrm{kg/m}^3)$.

Equation (4) shows that the relationship between the thermal capacity and thermal resistance of the specific material with equal cross-sectional areas is linear and has identical slope of the cumulative structure function. In other words, whenever the specific material or cross-sectional area is changed, the slope of the cumulative structure function also changes. Equation (5) shows that the amplitude of the differential structure function $\rho(R)$ is not related to the thermal resistance but the material and geometric parameters. The interface between different materials or different cross-sectional areas can be identified through the inflection point in the differential structure function because the inflection point indicates the junction of different materials or different cross-sectional areas.

The transient thermal-impedance curve of collector-side cooling under the rated clamping force (@ 1 kN) was measured, and the cumulative and differential structure functions are shown in Fig. 12. The horizontal axis denotes the sum of the thermal resistance in the heat flow path of the submodule. Along the direction of the thermal-resistance increase, the thermal resistances are in the sequence of the FRD chip resistance, thermal contact resistance between chip and molybdenum, molybdenum thermal resistance, thermal contact resistance between molybdenum and the collector pole, collector pole thermal resistance and other external thermal resistance (short for heatsink thermal resistance).

The dimensions of the studied FRD chip in this paper are 13.53 mm × 13.53 mm × 0.41 mm, and its measured thermal conductivity is 117.5 W/(m·K). Hence, the theoretical thermal resistance of the FRD chip is 0.019 K/W. It conforms with good accuracy to the measured 0.02 K/W. The results indicate that both bulk thermal resistance of specific material layers and thermal contact resistance between specific layers can be clearly identified.

The junction-to-case thermal resistance of the single FRD chip submodule obtained using the cumulative structure function is 0.5588 K/W, which is assumed to be the theoretical value in this paper. Assuming the theoretical value sets as the basis, the deviation of the traditional thermocouple method and the transient dual interface method is 6.9% and −4.2%, respectively. The experimental result of the traditional thermocouple method is slightly higher than the theoretical value, and the transient value is slightly lower but much closer to it.

IV. Conclusion

In this paper, both traditional thermocouple and transient thermal-impedance methods are proposed to measure the junction-to-case thermal resistance of the single FRD submodule to verify a suitable method for PP IGBTs. The preliminary conclusions are as follows.

1) Because of the external clamping constraint and the high temperature generated by the FRD chip during the test, the junction-to-case thermal resistance of the submodule and the junction temperature of the FRD chip decrease with repeated measurements and tend to eventually stabilize. Meanwhile, the clamping force has a dramatic influence on the junction-to-case thermal resistance of PP IGBTs because that the thermal contact resistance between various layers is affected by it.
2) The traditional thermocouple method is good for the junction-to-heatsink thermal resistance measurement instead of the junction-to-case of PP IGBTs with the limits of their packaging style and working conditions. However, as we know, if only the junction-to-heatsink thermal resistance is provided, the different cooling system between the measurement and application makes it difficult for users to take full advantage of it. The most important aspect of the traditional thermocouple method is the accurate measurement of the case temperature, so the electrode pole or heatsink should be customized if we want to measure the junction-to-case thermal resistance of PP IGBTs. The customized electrode pole or heatsink increases the cost and difficulty of this experiment. Most importantly, it is notably difficult to ensure that the thermocouple actually measures the case temperature and not the temperature of the heatsink or an average value in between.
3) The transient dual interface method does not require a thermocouple to measure the case temperature, which is an excellent advantage to compensate for the shortcomings of the inability of PP IGBTs to locate a thermocouple. However, two important factors significantly affect the accuracy of the transient method in measuring the junction-to-case thermal resistance of PP IGBTs. One of the important factors is the clamping force, which affects the thermal contact resistance between the case and heatsink and within PP IGBTs. The different clamping forces between those two transient thermal-impedance curves measurements change the thermal contact resistance within PP IGBT and eventually cause an earlier splitting point. It is also notably important to handle the interface condition because the improper interface condition will cause an overlap of those two curves, and the splitting point is not obvious to identify the junction-to-case thermal resistance. Therefore, strictly maintaining the clamping force of the studied PP IGBT in consistency and proper handling of the interface are notably important to the transient dual interface method for PP IGBT's measurement.
4) The traditional thermocouple method is not suitable to measure the junction-to-case thermal resistance of PP IGBTs with the disadvantages of overestimating the value and requiring a thermocouple to locate into the case surface. The transient dual interface method can more rapidly obtain the junction-to-case thermal resistance of PP IGBTs, which is closer to the actual value. Meanwhile, both bulk thermal resistance of specific material layers and thermal contact resistance between specific layers can be clearly identified using the transient method.

In summary, the transient dual interface method is suitable to measure the junction-to-case thermal resistance of PP IGBTs.

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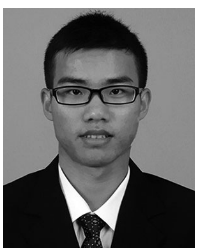

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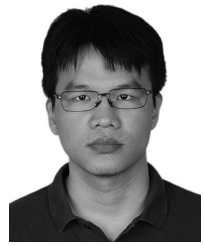

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