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Multi-physics field simulation of electro-thermal-stress of IGBT device based on Al/Diamond material

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***Abstract*—Insulated Gate Bipolar Transistor (IGBT) is the core component of current converter equipment in application scenarios such as flexible DC transmission and flexible AC transmission, and its junction temperature increases significantly with the increase of current level. Therefore, the junction temperature control of IGBT devices has become one of the bottlenecks to further increase the transmission capacity. Al/Diamond material has a much higher thermal conductivity than traditional packaging materials and a smaller coefficient of thermal expansion, so applying Al/Diamond material to IGBT packaging may improve the heat dissipation ability of IGBT and thus reduce the junction temperature. This paper constructs the IGBT model based on Al/Diamond material and the IGBT model based on traditional copper material through COMSOL simulation software, and compares the internal electro-thermal-stress distribution of the two models. In addition, this paper calculates the maximum and average values of temperature, maximum and average values of thermal stress and other parameters of each component inside the model according to the simulation data set. After comparison, it can comprehensively reflect the greater enhancement of heat dissipation capability of IGBT after applying Al/Diamond material to its encapsulation, which provides guidance for the subsequent research on the encapsulation optimization mechanism of high-power IGBT devices based on Al/Diamond material and the actual device fabrication.**

Keywords-IGBT; Al/Diamond; multi-physics field; copper; thermal stress; heat conductivity

I. INTRODUCTION

In the "double carbon" strategic objective and the new power system construction of the dual background, IGBT and other switching devices such as high-voltage and large-capacity flexible AC/DC converter equipment will be a wider range of applications [1], its voltage level and converting capacity will be further enhanced. Its voltage level and current converting capacity will be further improved. As the core device of the converter equipment, the junction temperature of high-power IGBT will be greatly increased with the increase of current level, and its heat dissipation and junction temperature control capability has become one of the bottlenecks for the further increase of converting capacity [2-3]. Al/Diamond material has much higher thermal conductivity than conventional packaging materials [4]. And as a heat transfer structural member in the device packaging structure, it may have significant advantages in enhancing the power density of IGBT devices, reducing the chip junction temperature and improving the transmission capacity. Therefore, this paper constructed the IGBT device model based on Al/Diamond material and the IGBT device model based on copper material through COMSOL simulation software, and set the boundary conditions and multi-physics fields, and compared and investigated the characteristics of the internal electro-thermal-stress distribution of the two IGBT device models. Moreover, this paper calculated the electrical-thermal-force related values through the simulation data set, which comprehensively demonstrated that the application of Al/Diamond material to IGBT devices can enhance the heat dissipation ability of IGBT and thus reduce the probability of IGBT failure.

II. AL/DIAMOND MATERIAL PROPERTIES

Al/Diamond, also known as diamond particle reinforced phase aluminum matrix composites, is a particle reinforced phase metal matrix composite formed by uniformly dispersing diamond particles into aluminum, which combines the advantages of aluminum and diamond materials [5-7]. Al/Diamond composites are metal matrix composites with aluminum metal as the matrix and diamond as the reinforcing phase. The thermal conductivity of the single-crystal diamond used therein is as high as 1500~2000 W/(m·K), which is about four to five times of the thermal conductivity of metallic copper, while the coefficient of thermal expansion is only 1.2×10-6/K, which provides a unique advantage in the field of thermal management [8]·Meanwhile, with the development of synthetic diamond technology, the price of diamond particles has been greatly reduced, making it possible for diamond-based composites to be widely used. Due to the utilization of the excellent properties of diamond, Al/Diamond composites are characterized by low density, controlled coefficient of thermal expansion, and high thermal conductivity compared with conventional encapsulation materials (as shown in Fig 1 and Table I).

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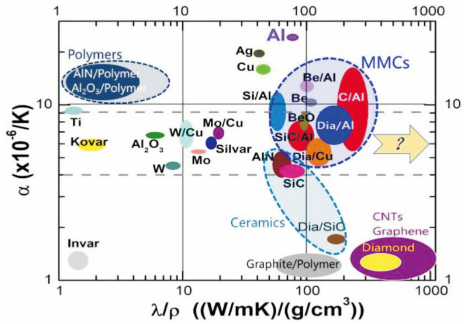


Figure 1. Thermal Conductivity-Thermal Expansion Coefficient Distribution of Commonly Used Thermal Management Materials [9].

TABLE I. PROPERTIES OF METAL AND METAL-BASED ENCAPSULANTS [10-11]

material	thermal conductivity /($W \cdot m^{-1} \cdot K^{-1}$)	CTE /($10^{-6}K^{-1}$)	density /($g \cdot cm^{-3}$)
Al	221	23	2.7
Cu	400	17.7	8.9
Degradable alloys	17	5.8	8.3
Tungsten-copper alloy	190	6	7.3
silicon Al carbide	185	6.5	2.85
Co Diamond	600	5.8	5.7
Aluminum Diamond	550	7	3

From Table I, it can be seen that although the metallic materials aluminum and copper have high thermal conductivity, the CTE is too high compared to semiconductor materials, which tends to cause large thermal stress. Degradable alloys have a CTE that matches semiconductor materials, but the thermal conductivity is too low to meet the demands of thermal management. Tungsten-copper alloys and aluminum silicon carbide materials have improved thermal conductivity and CTE, but both have thermal conductivity below 200W/(m·K), making it increasingly difficult to meet the requirements of highly integrated, high heat-flow density packaging. Copper diamond and Al/Diamond materials are all new materials with high thermal conductivity of diamond as the reinforcing phase, thermal conductivity can reach more than 500W/(m·K), and has a small CTE, is a good comprehensive performance of the packaging material. Among them, the density of Al/Diamond material is small, especially suitable for application in key areas such as encapsulation, aerospace and military. In summary, Al/Diamond material has good thermal conductivity and low coefficient of thermal expansion, and its application in IGBT can effectively enhance the heat dissipation ability of IGBT and thus reduce the junction temperature. However, at present, we are only limited to the theoretical analysis of material properties and have not applied the Al/Diamond material to IGBT for simulation analysis, so it is necessary to construct an IGBT model based on Al/Diamond material and then study the internal multi-physics field.

III. COMSOL-BASED MULTI-PHYSICS FIELD SIMULATION STUDY OF IGBT

A. IGBT Module Structure

At present, the IGBT module structure on the market has crimped and soldered, the majority of high-power IGBT sold on the market and engineering applications for the modular package. Therefore, the research object of this thesis is the welded IGBT module. The structure of an IGBT half-bridge module is shown in Fig 2. Inside the model from top to bottom is the external interface, silicon potting adhesive, bonding line, chip, chip solder layer, DBC substrate, substrate solder layer, thermal grease, heat sink.

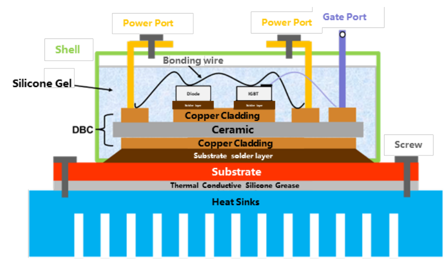
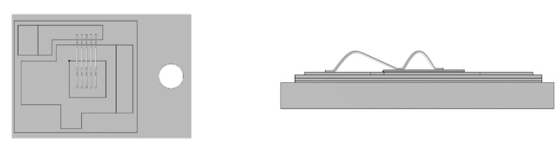


Figure 2. Welded IGBT module structure [12]

B. IGBT Modeling and Simulation Setup

According to the structure of the welded IGBT module described in Fig 2, I constructed the IGBT 3D model based on COMSOL multi-physics field simulation software, as shown in Fig 3. Considering the model complexity will COMSOL software simulation rate, so do not build the diode model, IGBT shell, thermal conductive silicone grease, heat sink and other structures. Fig 3 shows the structure from top to bottom are: bonding wire, metallized aluminum layer, chip solder layer, substrate backplane solder layer, heat sink backplane.



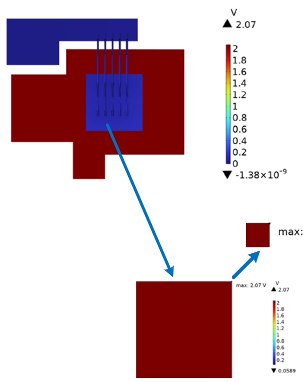
a) Top view of IGBT model b) Front view of IGBT model

Figure 3. IGBT 3D Simulation Model

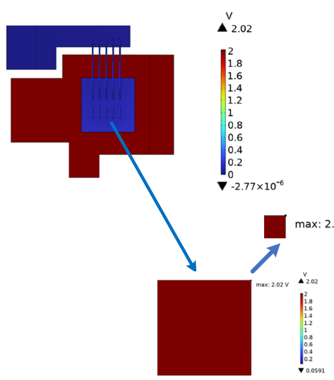
After the model is established, boundary conditions and multi-physics fields need to be set for the actual situation. According to the relevant literature research, the internal IGBT device is mainly affected by electric-thermal-force interaction [13-14]. Therefore, the physical fields of the model built in this paper are selected as current field, solid heat transfer field, solid mechanics field, and set the mutual coupling between electricity and heat, and the mutual coupling between heat. The boundary conditions are set as follows: the collector is 70A, and the emitter is grounded; the overall initial temperature is 293.15K; the chip, bonding wires, the chip solder layer, and the DBC solder layer are put into a "free state". "which is subjected to thermo-mechanical stresses.

C. Comparison of Electro-Thermal-stress Multi-Physics Field Simulations Results

This subsection focuses on the comparative analysis of the internal electro-thermal-stress distribution of the IGBT model based on copper substrate material and the IGBT model based on Al/Diamond material. The overall potential comparison inside the two IGBT models is shown in Fig. 4.



a) Overall distribution of copper substrate IGBT device and chip potential distribution

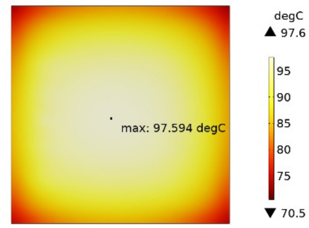


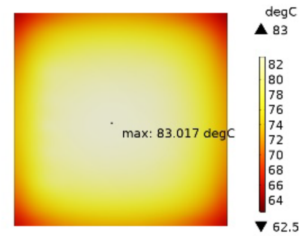
b) Al/Diamond substrate IGBT device overall distribution and chip potential distribution

Figure 4. Comparison of internal potentials of two IGBT models

As shown in the fig above, the overall potential distribution and chip potential distribution of the two IGBT models are almost the same, which is due to the fact that the current is set in the upper copper layer and the chip and bonding wire area, which has little to do with the heat dissipation substrate.

Al/Diamond material is used in IGBT thermal substrates due to its high thermal conductivity and high heat dissipation capability. Therefore, in order to investigate the enhancement of Al/Diamond material on the heat dissipation ability of IGBT devices, the internal heat distribution of IGBT model in simulation should be our focus. The following is a comparison between the copper-based IGBT model and the Al/Diamond-based IGBT model in terms of internal chip temperature distribution, bonding wire temperature distribution, and so on.



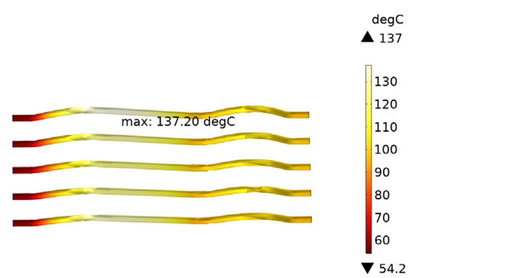


a) Copper substrate IGBT device chip temperature distribution b) Al/Diamond substrate IGBT device chip temperature distribution

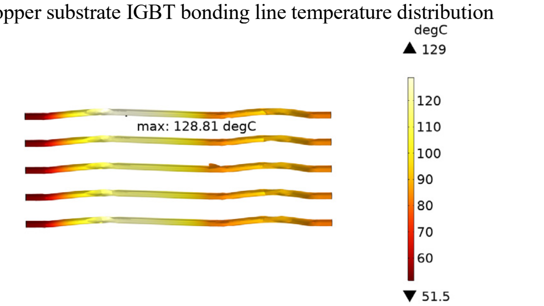
Figure 5. Comparison of chip temperature of IGBT devices with two materials

According to Fig 5, it can be seen that the temperature distribution of the IGBT chips of both materials is large in the center and small in the surroundings. The maximum temperature of the IGBT chip based on Al/Diamond material is 83.017degC, while the maximum temperature of the IGBT chip based on copper material is 97.594degC, which is a difference of 14.57degC.

However, it is not enough to observe the temperature distribution of the chip only. According to the existing literature, the temperature fluctuation of bonding wires and solder layers due to changes in operating conditions, the mismatch of the thermal expansion coefficients of the upper and lower layers, which causes the phenomena of broken bonding wires, detachment, and cavities in the solder layer, ultimately lead to the failure of IGBT [15]. Therefore, a comparative study of the temperatures of the bonding wires and solder layers inside the two models is very necessary. As shown in Fig. 6, the two graphs show the comparison of bonding wire temperatures between the IGBT device based on Al/Diamond material and the IGBT device based on copper material, respectively.



a) opper substrate IGBT bonding line temperature distribution

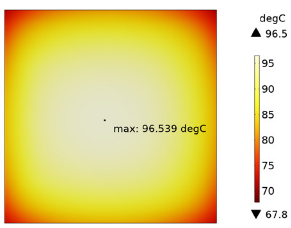


b) Al/Diamond substrate IGBT device bonding line temperature distribution

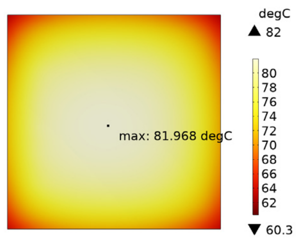
Figure 6. Comparison of bonding wire temperatures of IGBT devices with two materials

From Fig. 6, it can be seen that the maximum temperature of the bonding line of the IGBT device based on copper material is 137.20degC, and the maximum temperature of the bonding line of the IGBT device based on Al/Diamond material is 128.81degC, with a difference of about 8.39degC. In addition, as can be seen in Fig. 6, the left measurement prongs of the bonding wires of both models are clearly marked with depression marks. It may be due to the mismatch between the thermal expansion coefficient of the bondling wire and the chip and the thermo-mechanical stress on the bondling wire.

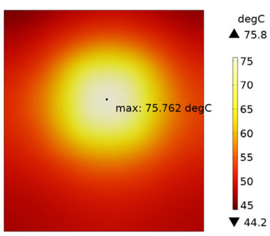
The solder layer is also one of the weak points of the IGBT package. As shown in Fig 7, the two graphs show the comparison of the temperature distribution of the chip solder layer and the substrate solder layer between the IGBT device based on Al/Diamond material and the IGBT device based on copper material, respectively.



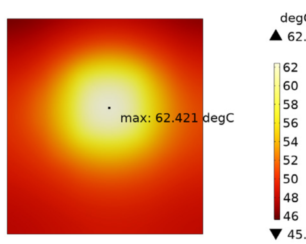
a) Copper substrate IGBT device chip solder layer temperature distribution



b) Al/diamond substrate IGBT device chip solder layer temperature distribution



c) Copper substrate IGBT device substrate solder layer temperature distribution

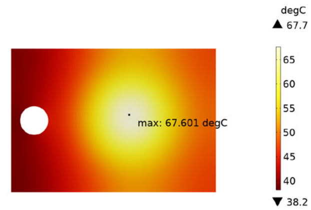


d) Al/diamond substrate IGBT device substrate solder layer temperature distribution

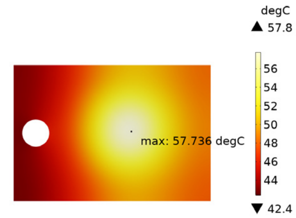
Figure 7. Comparison of solder layer temperature distribution of IGBT devices with two materials

As can be seen from graphs a and b of Fig. 7, the maximum temperature of the solder layer of the IGBT device chip based on copper material is 96.539degC, and the maximum temperature of the solder layer of the IGBT device chip based on Al/Diamond material is 81.968degC, with a difference of about 14.571degC. As can be seen from graphs c and d of Fig. 7, the maximum temperature of the solder layer of the IGBT device chip based on copper material is 75.762degC, and the maximum temperature of the IGBT device chip based on Al/Diamond material is 62.421degC, with a difference of about 14.341degC. In summary, the temperature of the internal bonding line and the solder layer of the Al/Diamond material used in the IGBT decreases compared with that of the ordinary copper material.

Both materials are mainly used in IGBT thermal substrates, so the comparison of the thermal substrate temperature is also very necessary. As shown in Fig. 8, the two graphs show the shell temperature comparison between the IGBT device based on Al/Diamond material and the IGBT device based on copper material, respectively.



a) Copper substrate IGBT device shell temperature distribution



b) Al/Diamond substrate IGBT device shell temperature distribution

Figure 8. Comparison of solder layer temperature distribution of IGBT devices with two materials

From Fig. 8, a, b, it can be seen that the maximum value of the shell temperature of the IGBT based on copper material is 67.601degC and the maximum value of the shell temperature of the IGBT device based on Al/Diamond material is 57.736degC, which is a difference of 9.865degC. Fig 5, 6, 7 and 8 only compare the maximum temperature difference of each component of the IGBT, ignoring the comparison of the average temperature of each component. In COMSOL software, the results of the simulation are placed in a dataset, through which the average temperature is calculated. As shown in Table II and Table III, the maximum and average temperatures of each component within the two models are presented in a list and the difference is calculated. In order to facilitate the list layout, set the maximum value of the chip temperature as T_{jmax}, the average value is T_{jave}; the maximum value of the bonding wire temperature is T_{bmax}, the average value is T_{bave}; the maximum value of the shell temperature is T_{cmax}, the average value is T_{cave}, the maximum value of the chip solder layer temperature is T_{clmax}, the average value is T_{clave}; the maximum value of the substrate solder layer temperature is T_{slmax}, the average value is T_{slave}.

TABLE II. DATA SET TEMPERATURE CALCULATIONS (1)

IGBT Substrate	T_{jmax} (degC)	T_{jave} (degC)	T_{bmax} (degC)	T_{bave} (degC)	T_{Cmax} (degC)	T_{Cave} (degC)
Cu	97.594	88.874	137.20	101.18	67.601	49.149
Al/Diamond	83.017	76.485	128.81	91.087	57.736	48.467
difference	14.577	12.389	8.390	10.093	9.865	0.682

TABLE III. DATA SET TEMPERATURE CALCULATIONS (2)

IGBT Substrate	T_{clmax} (degC)	T_{clmax} (degC)	T_{slmax} (degC)	T_{slave} (degC)
Cu	96.539	87.676	75.762	54.342
Al/Diamond	81.968	75.315	62.421	51.187
difference	14.571	12.361	13.341	3.155

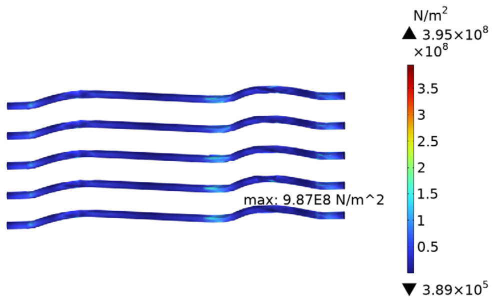
From the differences in Table II and III, it can be seen that T_{max} or T_{ave} of the temperature of each layer of the IGBT devices based on copper material is almost always 3dedgC and more than that of the IGBT devices based on Al/Diamond material. It indicates that the overall temperature of the IGBT device based on Al/Diamond material is smaller and has better heat dissipation capability. Among them, the shell temperature difference between the two materials is the largest, indicating that the Al/Diamond material substrate has better heat dissipation performance.

The heat generated by the current subjects the IGBT components to thermal-mechanical-stress that may have an impact on the IGBT lifetime. Plastic strain occurs when the mechanical stress exceeds the initial yield stress of the material, and this strain results in permanent deformation of the material, which remains even after the thermal stresses have disappeared [16]. Metallic materials with viscoplastic properties will still slowly deform plastically, or creep, when the stress is less than the yield stress. Creep of metals is related to stress, temperature and time. The creep strain of a viscoplastic material can be described by the Garofalo hyperbolic sine model [17]:

$$\dot{\varepsilon}_{c} = A \cdot [\sinh S(\alpha \cdot \sigma)]^{n} \exp(-\frac{Q}{R \cdot T}) \qquad (1)$$

where $\dot{\varepsilon}_c$ represents the rate of creep, A is the creep rate coefficient, σ is the applied stress at which creep occurs, α is the inverse stress, R is the ideal gas constant, Q is the creep activation energy, and n is a parameter related to the material.

Therefore, a comparative study of the thermo-mechanical stress on the components of the two IGBT models is very important. Since it has been explained that the bonding wires and the solder layer in the IGBT device are easily affected by thermal stress, the following is a comparative analysis of the thermo-mechanical stress on the bonding wires and the solder layer of the two IGBT models, as shown in Fig. 9.

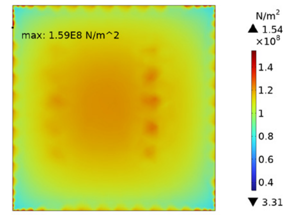


a) Copper substrate IGBT bonding wire thermal stress distribution

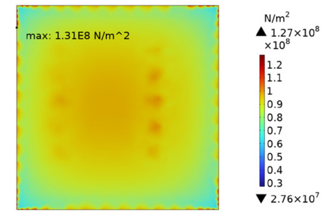
b) Al/diamond substrate IGBT bonding wire thermal stress distribution

Figure 9. Comparison of thermal stresses in bonding wires of IGBT devices with two materials

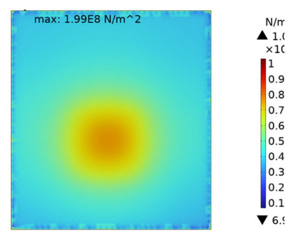
As can be seen from Fig. 9, the maximum thermal stress of the copper-based IGBT bonding wire is 9.87e8 N/m^2, and the maximum thermal stress of the Al/Diamond-based IGBT bonding wire is 5.22e8 N/m^2, with a difference of 4.65e8 N/m^2. It is probably due to the fact that the Al/Diamond-based IGBT bonding wires have a better heat dissipation performance, and the overall temperature of the bonding wire is much lower, so the thermo-mechanical stress on the wire are much lower, which may also reduce the risk of breakage and detachment. It may be due to the lower thermo-mechanical stress on the bonding wires because the overall temperature of the bonding wires is lower, which may also reduce the risk of bonding wire breakage and detachment. Fig. 10 shows a comparison of the thermal stress distribution of the chip solder layer and the substrate solder layer of the two models.



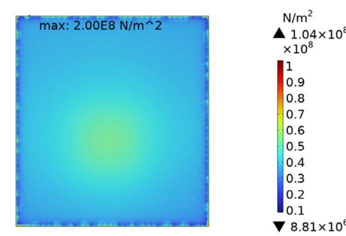
a) Thermal Stress Distribution in the Solder Layer of IGBT Device Chip on Copper Substrates



b) Al/diamond substrate IGBT device chip solder layer thermal stress distribution



c) Copper substrate IGBT device substrate solder layer thermal stress distribution



d) Al/diamond substrate IGBT device substrate solder layer thermal stress distribution

Figure 10. Thermal Stress Comparison of Chip Solder Layer and Substrate Solder Layer of IGBT Devices with Two Materials

As shown in Fig. 10, the maximum thermal stress in the solder layer of the copper-based IGBT device chip is 1.59e8 N/m^2, and the maximum thermal stress in the solder layer of the Al/Diamond-based IGBT device chip is 1.31e8 N/m^2, with a difference of 0.28e8 N/m^2. The maximum thermal stress in the solder layer of the copper-based IGBT device substrate is 1.99e8 N/m^2, and the maximum thermal stress in the solder layer of the Al/Diamond-based IGBT device substrate is 2.00e8 N/m^2, with a difference of 0.01 N/m^2. With the simulation data set, the average thermal stress of each component can be calculated as shown in Table IV and Table V. In order to facilitate the list layout, the bonding line is subjected to a maximum thermal stress of F_{bmax} and an average thermal stress of F_{bave}; the chip solder layer is subjected to a maximum thermal stress of F_{clmax} and an average thermal stress of F_{clave}; and the substrate solder layer is subjected to a maximum thermal stress of F_{slmax} and an average thermal stress of F_{slave}.

TABLE IV. DATASET THERMAL STRESS CALCULATION RESULTS (1)

IGBT Substrate	F_{bmax} (N/m^2)	F_{bave} (N/m^2)	F_{clmax} (N/m^2)
Cu	9.87e8	2.46e7	1.59e8
Al/Diamond	5.22e8	2.11e7	1.31e8
difference	4.65e8	0.35e7	0.28e8

TABLE V. DATASET THERMAL STRESS CALCULATION RESULTS (2)

IGBT Substrate	F_{clave} (N/m^2)	F_{slmax} (N/m^2)	F_{slave} (N/m^2)
Cu	1.09e8	1.99e8	4.65e7
Al/Diamond	8.81e7	2.00e8	3.81e7
difference	0.209e8	-0.01e8	0.84e8

From Table IV and Table V, it can be clearly seen that the thermo-mechanical-stress on almost all components of the IGBT devices based on Al/Diamond material are greater than those on the IGBT devices based on copper material. Therefore, the probability of thermal fatigue damage to the bonding wires and solder layer of the Al/Diamond material-based IGBT is smaller, and the probability of its failure is also smaller.

IV. CONCLUSIONS

This paper firstly describes the bottleneck of heat dissipation capacity enhancement encountered by IGBT devices with the development of new energy sources, and then after relevant literature research, it shows that Al/Diamond material has higher thermal conductivity compared with traditional materials. Therefore, Al/Diamond material is considered to be applied to IGBT devices to improve their heat dissipation and junction temperature control capability. This paper compares and analyzes the potential distribution, temperature distribution, and thermal stress distribution of the IGBT model based on aluminum diamond material and the IGBT model based on copper material by means of electric-thermal-force multi-physics field simulation. Moreover, this paper also calculated the maximum and average temperature, maximum stress and average stress of each component of the IGBT through the simulation data set. After comparing the calculation results, the temperature of each component and the thermal stress suffered inside the IGBT model based on aluminum diamond material are smaller than that of the IGBT model based on copper material. It indicates that the use of diamond materials in IGBT devices can enhance their heat dissipation ability and reduce the chip junction temperature. At the same time, this can also reduce the thermal stress on each component of the IGBT, thus reducing the probability of IGBT failure. However, this article mainly analyzes the electro-thermal stress distribution of each component inside the IGBT from the perspective of steady state simulation, and does not conduct transient simulation to analyze the temperature fluctuation and thermo-mechanical stress fluctuation of each component inside the IGBT. Secondly, there is a big difference between the simulation effect and the experimental effect. To check whether applying a new heat dissipation material to IGBT devices can improve the heat dissipation capability of IGBTs, it is necessary to analyze it from two different dimensions by combining simulation and experiment.

Therefore, it is necessary to carry out transient simulation to observe the temperature fluctuation and thermal stress fluctuation of each component inside the IGBT. Moreover, the relevant units should carry out power cycle test and relevant temperature test after making the IGBT devices based on aluminum diamond material, so as to illustrate the enhancement of heat dissipation ability of IGBT devices by applying aluminum diamond material to them from the experimental data combined with the simulation results.

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