Chapter 5

Clamping Force Distribution within Press Pack IGBTs

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Additional information is available at the end of the chapter

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Abstract

Press pack insulated gated bipolar transistors (PP IGBTs) have been gradually used in the high-voltage and high-power-density applications, such as the power system and electric locomotive, with its advantages of double-sided cooling, higher power density, and easy to connect in series compared with traditional wire-bonded power IGBT modules. However, the clamping force is quite important for PP IGBTs because too much clamping fore will cause mechanical damage to the silicon chips and too little clamping force will increase the junction temperature of the silicon chips due to the increased thermal contact resistance. And eventually it leads to thermal damage. Furthermore, the clamping force distribution within PP IGBTs is affected by many factors, and they can be divided into the internal and external factors. The finite element analysis model of the PP IGBTs is established based on the theory of elastic mechanics to obtain the influence of the affect factors, including the external clamping modes, spring design, thermal stress, the machining accuracy, and so on. The contribution of those affect factors to the clamping force distribution is ranked, and this can be a guideline not only for users but also for the manufacturers.

Keywords: flexible HVDC, press pack IGBTs, clamping force distribution, reliability, affect factors

1. Introduction

1.1. Opportunities for PP IGBTs

Nowadays, the challenges such as globally increasing demand of electrical energy, the stringency of conventional energy resources (such as oil, gas, and coal), and so on are arising in the field of electrical energy supply [1]. The high-voltage direct current (HVDC) transmission system, especially the flexible HVDC transmission system with voltage source converters (VSC), is an innovative solution because of its advantages of the ability to supply the power to the passive power grid (i.e., islet), the independent control of the active and reactive power, and the flexible operation modes [2]. The most important parts of the flexible HVDC transmission system are the converter valve and HVDC breaker, which are based on Insulated Gate Bipolar Transistors (IGBTs), briefly shown in **Figure 1**.

The flexible HVDC transmission system has been successfully applied in the developed countries for many years, and it is prosperous in China in the recent years. More and more projects with higher voltage and higher capacity ratings are developing to meet the requirements and the reliability as the most important issue. This high-voltage and high-reliability application has greatly promoted the development of IGBTs. There are two packaging styles for high-power IGBT devices: typical wire-bonded IGBT modules and press pack IGBTs (PP IGBTs). The high-power IGBT module of 3300 V/1500 A had been widely used in the flexible HVDC transmission system. While with the growing demand of capacity, the IGBT module cannot meet the increasing voltage and capacity requirements, and PP IGBTs are gradually applied with its advantages of higher-power density, easy to connect in series, and short-circuit failure mode [3].

The first PP IGBTs used in the converter valve of the flexible HVDC transmission system in China is 4500 V/1500 A. After this, PP IGBTs of 3300 V/2000 A, 3300 V/3000 A, 4500 V/2000 A, and 4500 V/3000 A are required in the future flexible project because of the higher capacity demand, for example, the 4500 V/3000 A is needed in the 500 kV/3000 MW or 800 kV/3000 MW flexible project.

1.2. Challenges for PP IGBTs

The press pack packaging style for high-voltage and high-power density IGBT can be divided into StakPak (**Figure 2**) and press pack (**Figure 3**). The original motivation in most cases was the poor power-cycling capability of early versions of wire-bonded modules and their explosion behavior [5]. The StakPak packaging style is patent protected by ABB, and the research on the StakPak is very limited. The press pack is widely used by Poseico, Fuji, Westcode, and Toshiba because of the experience with the packaging of high-power devices, such as gate turn-off thyristors, diodes, IGCT, and so on [6], and many researches are based on this packaging style. Therefore, the PP IGBTs discussed in this chapter are the press pack style as shown in **Figure 3**.

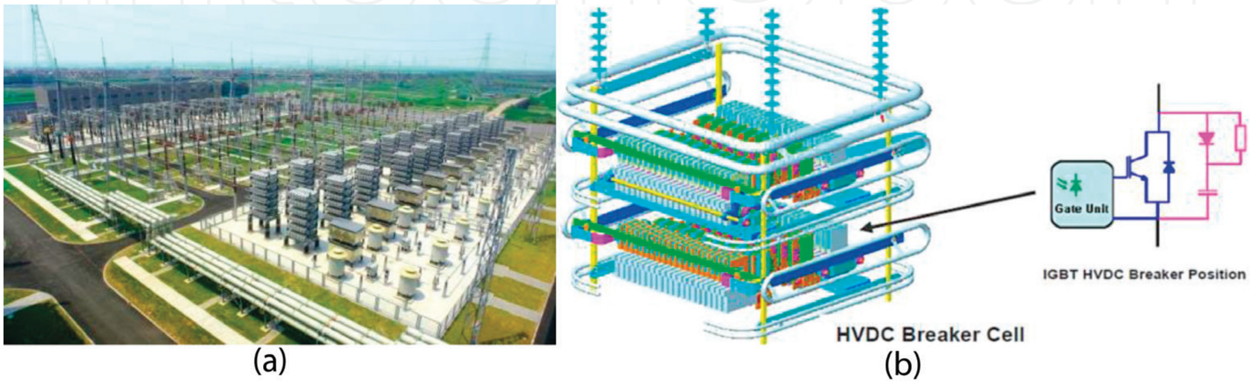

Figure 1. Two most important components in the flexible HVDC transmission system: (a) converter valve station and (b) schematic diagram for HVDC breaker [4].

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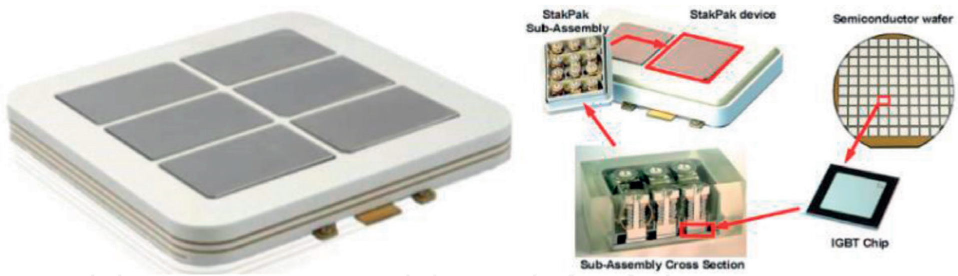

Figure 2. StakPak packaging style from ABB.

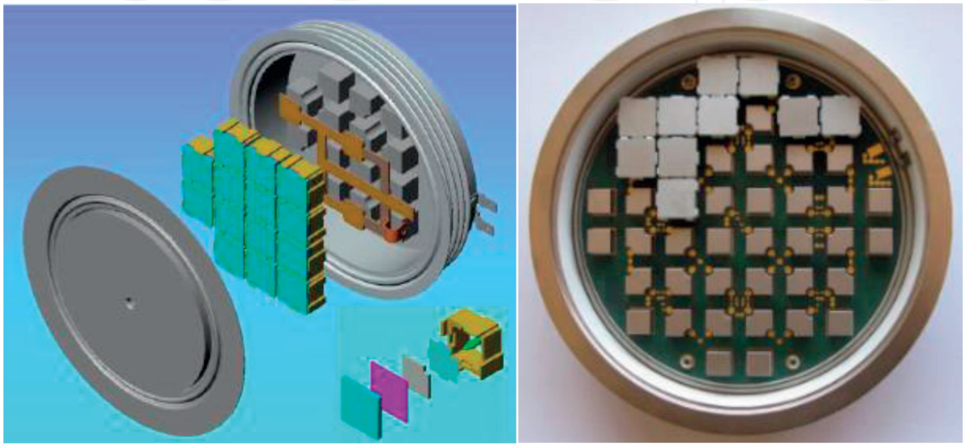

Figure 3. Press pack packaging style from Westcode [7].

Figure 3 shows that the PP IGBTs have a multilayered structure. The electrical and thermal paths for the silicon chips are supplied by the collector and emitter copper electrodes. Furthermore, the needed clamping force also should be applied on the two electrodes to make all components to contact well. The recommended clamping force for applications in a datasheet is a range, and a clamping pressure of 1.2 kN/cm^2 is ideal according to mounting instructions from manufacturers [8, 9]. Two molybdenum plates surrounding the silicon chips are to uniform the clamping force distribution and reduce the thermal expansion/contraction between the molybdenum plates and silicon chips when the press pack IGBT undergoes high-temperature variations. A silicon chip subassembly is consisted of a silver shim plate, together with a silicon chip and two molybdenum plates. Many silicon chip subassemblies connected in parallel to form a press pack IGBT and the current rating is determined by the paralleled number.

With the increasing demand of higher voltage and current ratings, more and more silicon chip subassemblies are needed to connect in parallel. Therefore, there are many challenges in the packaging technology, especially the long life time reliability when applied in the flexible HVDC transmission system as follows:

- current distribution among silicon chips [10];
- clamping force distribution among silicon chips [11–13];
- junction temperature distribution among silicon chips [14];

- the internal insulation problem [15];
- long-time reliability [16].

1.3. Clamping force distribution

For PP IGBTs, the clamping force is a special and very important parameter that many other parameters are correlated with this value, including the electrical and thermal behavior, reliability, and so on. For example, the current and junction temperature distributions are affected by the clamping force distribution a lot [17] through the electrical and thermal contact resistance [18, 19]. Too much clamping force will mechanically damage the silicon chip and too little clamping force will increase the junction temperature caused by the increased thermal contact resistance. Eventually, this leads to the silicon chip thermal damage as shown in **Figure 4** [20]. Therefore, the clamping force distribution within PP IGBTs is quite important that it not only affects both the electrical and thermal behavior but also the long-time reliability of PP IGBTs.

There are many factors that may influence the clamping force distribution within PP IGBTs not only during the design process but also in the applications. And the affect factors can be divided into external and internal factors. All the factors that may affect the clamping force distribution within PP IGBTs are shown subsequently and analyzed through the finite element method. For high-power IGBT modules or PP IGBTs, some Fast Recovery Diode (FRD) chips are always connected in anti-paralleled with the IGBT chips to provide the current path while the IGBT chips are turned off. Actually, the matching of the silicon chips, which means the internal layout of IGBT chips and FRD chips within PP IGBTs, will also influence on the clamping force distribution. However, the electrical and thermal behaviors, for example, the collector current and junction temperature distributions, of the PP IGBTs depend on the internal layout or matching of the silicon chips to a large extent. Therefore, the matching of the silicon chips should pay more attention to the electrical and thermal behaviors rather than the clamping force distribution.

A. External affect factors

- external clamping modes
- design of disc spring

B. Internal affect factors

- slim plates
- thermal stress
- machining accuracy
- internal layout
- design of electrodes

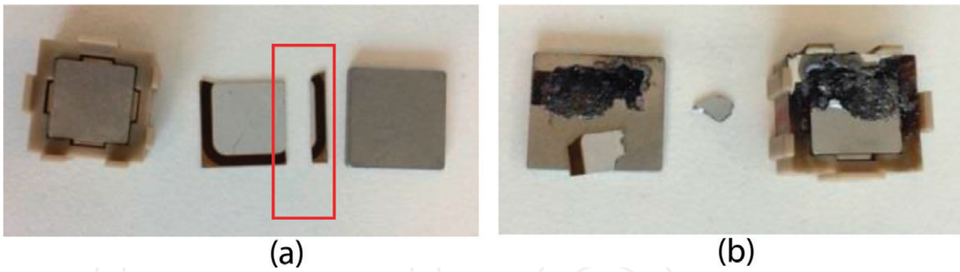

Figure 4. Failed silicon chips caused by nonuniform clamping force [20]: (a) too much pressure and (b) too little pressure.

2. Basic theory

2.1. Governing equations

Mechanics is a very useful discipline established to explain many phenomena existing in nature, for example, material mechanics, structure mechanics, elastic mechanics, elastic–plastic mechanics, and so on. Material mechanics is mainly used to explain the deformation of a single simple object. Elastic mechanics can be used to research the micro-deformation phenomenon, and elastic–plastic mechanics is mainly used to explain the macro-deformation, for example, nonlinearity, material yield problem, and so on.

PP IGBTs consist of many components that undergo micro-deformation as stated before, thus the elastic mechanics is suitable for its mechanical analysis. The mechanical analysis of a specific material can be explained through the physical properties of materials, deformation, and the balance of forces. Just like in the electrical engineering area, Maxwell's equations can be used to explain all electromagnetic phenomena. Coupled with specific boundary conditions, three equations, including the constitutive equations of materials, geometric equations, and equilibrium equations of force as shown in Eqs. (1)–(3), are used to solve all the elastic mechanics problems:

$$-\nabla \cdot \sigma = F \tag{1}$$

$$\sigma = E \cdot \varepsilon \tag{2}$$

$$\varepsilon = \nabla \cdot u \tag{3}$$

where σ is stress, F is external force, E is elasticity modulus, ε is strain, and u is displacement.

2.2. Finite element model

Eqs. (1)–(3) can be used to explain all the elastic mechanics phenomena, and the equations without specific boundary conditions have unbounded solution. But for engineering problems, there must be a specific solution. Thus, we need to appoint the boundary condition for engineering problems to get the unique solution. In this chapter, the finite element model of PP IGBTs is proposed to predict the clamping force distribution under different conditions and

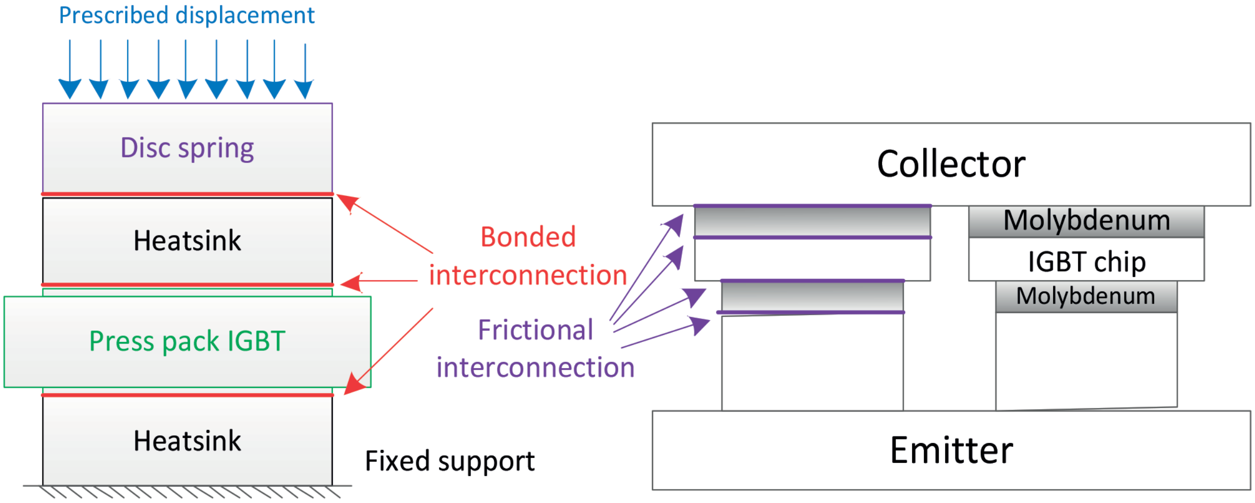

Figure 5. Boundary conditions of the mechanical model.

the boundary conditions are set as follows. In the application of PP IGBTs, a force spreader or a clamp stack is used to transmit the clamping force to the heatsink and then transfer from the heatsink to the surface of the PP IGBTs. A disc spring, usually changing several mm under the clamped phase, is needed to compensate the physical movements, usually several μm, during the process of clamping and thermal expansion. To approximate the working conditions, a prescribed displacement, which is equivalent to the rated clamping force, is applied to the disc spring on the surface of the heatsink of the PP IGBT collector side. A fixed support is placed on the surface of the heatsink of the PP IGBT emitter side. The simplified diagram of the boundary conditions for the mechanical model is shown in **Figure 5**. The mechanical model should also consider the frictional interconnections among the different layers. The interconnections between heatsinks and PP IGBT are set as the bonded interconnection, and the interconnections between multilayers within PP IGBT are set as a frictional contact. A friction coefficient of 0.5 is assumed for the contact layers within the PP IGBT [21, 22], because the friction coefficient has little influence on the pressure distribution [23]. All finite element models used in this chapter to analyze the clamping force distribution within PP IGBTs, with the exception of the specified models, are set as in **Figure 5**.

3. External affect factors

Among the factors that may affect the clamping force distribution within PP IGBTs, we defined the factors from the applications or should pay attention in the applications or the factors outside of the PP IGBTs as the external affect factors. In the application of PP IGBTs, there exist two external factors that may affect the clamping force distribution a lot: external clamping modes and the design of disc spring.

3.1. External clamping modes

The press pack packaging style for IGBTs is learned from thyristors, IGCT, and so on, thus the clamping fixture to supply the needed clamping force in application is also the same. A force spreader is used to transmit the clamping force to the heatsink and then transfer from the heatsink to the surface of the PP IGBTs as shown in **Figure 6**. The disc spring is also needed to compensate the displacement during the clamping phase, and this parameter will be analyzed in the next part.

The force spreader is quite important in the clamping fixture for the press pack packaging style devices to transmit the uniform clamping force on the devices. Different from those devices with the whole wafer, like thyristors, IGCT, and so on, PP IGBTs contain multi-chips which are connected in parallel to improve the current rating. The uniform of the clamping force on the surface of PP IGBTs will greatly influence the clamping force within PP IGBTs and lower the reliability. Thus, the design of the force spreader is quite important to ensure its basic functions and improve the reliability of the whole system.

According to the basic principle of elastic mechanics, there are two boundary conditions to solve the elasticity problems: force load and displacement load. Force load is the most used boundary condition in the finite element simulations. Most of the studies that focus on the clamping force distribution within PP IGBTs used the force load principle. However, the PP IGBTs clamped by the clamping fixture are restricted by the prescribed displacement. Which boundary condition is suitable for the mechanical analysis of PP IGBTs is unclear. Those two boundary conditions directly applied on the surface of the PP IGBT are compared based on the finite element model mentioned earlier. Nine silicon chips are used as shown in **Figure 7**, and the clamping force of each silicon chip is shown in **Table 1**.

From the results, we can see that chip 5 located in the center of the PP IGBT has a relatively lower clamping force than other chips with the force load boundary condition, and the error is about −30.32%. As the study [19] shows, the thermal contact resistance existed in the contact interface within PP IGBTs depends on the clamping force to a large extent. Thus, the uniform clamping force distribution will influence the characteristic and reliability of PP IGBTs. However, the clamping force distribution within PP IGBT is relative even with the displacement of load condition that the maximum error is about 1.39%. In the real applications, the PP IGBTs are restricted by the prescribed displacement through clamping fixture. However, it is impossible to ensure a uniform displacement on the surface like the displacement load boundary

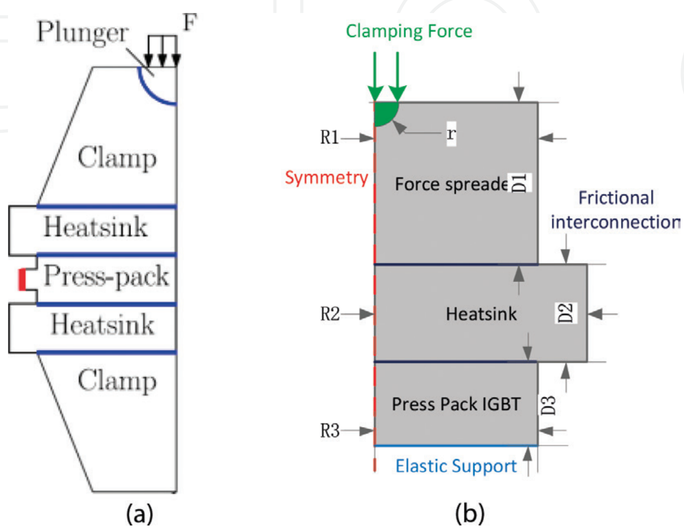

Figure 6. Simplified schematic diagrams for the clamping system: (a) structure diagram and (b) simulation diagram.

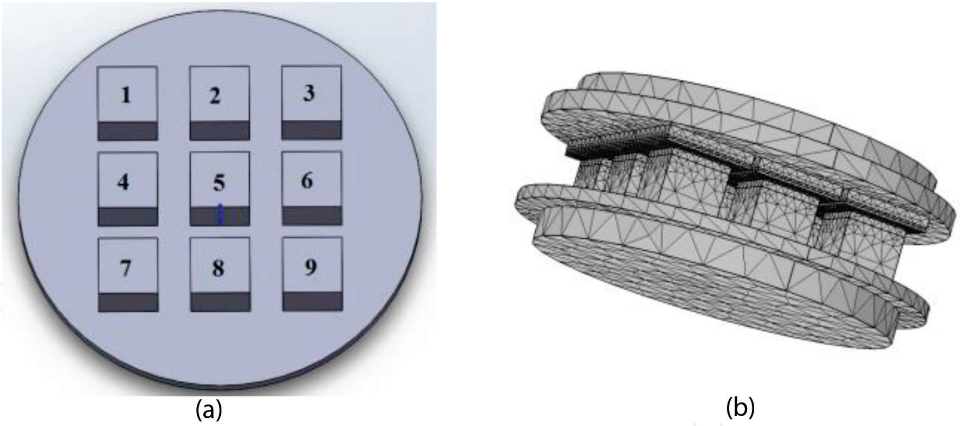

Figure 7. Finite element model: (a) chip number and (b) schematic diagram for simulation.

No	Rated (N)	Force (N)	Error (%)	Displacement (N)	Error (%)
1	1000	1074.6	7.46	986.06	−1.39
2	1000	1001.0	0.10	1010.1	1.01
3	1000	1073.5	7.35	987.06	−1.29
4	1000	1001.0	0.10	1009.7	0.97
5	1000	696.84	−30.32	1011.3	1.13
6	1000	1000.9	0.09	1010.4	1.04
7	1000	1076.1	7.61	987.39	−1.26
8	1000	1002.3	0.23	1011.9	1.19
9	1000	1073.8	7.38	986.09	−1.39

Table 1. Clamping force distribution under different boundary conditions.

condition. Furthermore, the clamping force will increase due to the thermal stress when the PP IGBT is heated up, and the force load condition is not suitable anymore in this situation.

The reason why the clamping force distribution within PP IGBT with force load conditions is worse than the displacement is because the displacement on the surface of PP IGBT is uneven. Therefore, the force spreader is designed to transmit the clamping force to the PP IGBT and ensure that the displacement on the surface is uniform. The clamping force distribution within PP IGBTs is related with the height of the force spreader as shown in **Figure 8** with the results of chip 5.

The radius of the studied PP IGBT is 28 mm, and as seen in **Figure 8**, the error of chip 5 trends to be stable when the height of the force spreader will be higher than 30 mm. That is to say, the displacement on the surface of the PP IGBT is relatively uniform and will not change with a higher force spreader. This is very important in the application. The height of the force spreader should be larger than the radius of the PP IGBT to ensure the clamping force distribution. And the error of chip 5 is still higher than the displacement load condition. However, the displacement load condition on the surface of PP IGBT or heatsink is too ideal.

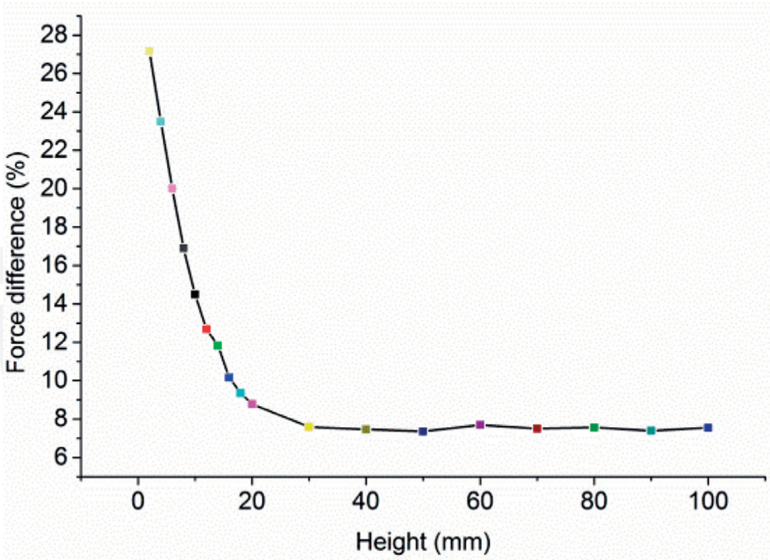

Figure 8. Relationship between the height of force spreader and error of chip 5.

Based on these results, it is shown that the design of the force spreader is quite important that the height of force spreader should be larger than the radius of the PP IGBT. Meanwhile, the clamping mode is very important in the finite element simulation. The best way is to apply the displacement load on the force spreader.

3.2. Design of disc spring

The disc spring is another quite important parameter in the application of PP IGBTs because it can not only compensate the displacement during clamping process but also absorb the thermal stress generated by the high temperature. Firstly, the importance of the disc spring is explained by the single IGBT chip submodule as shown in **Figure 9** under different conditions. One is the clamping phase that the submodule is just clamped by the fixture and another is the heating phase that the submodule is heated up with a desired clamping force.

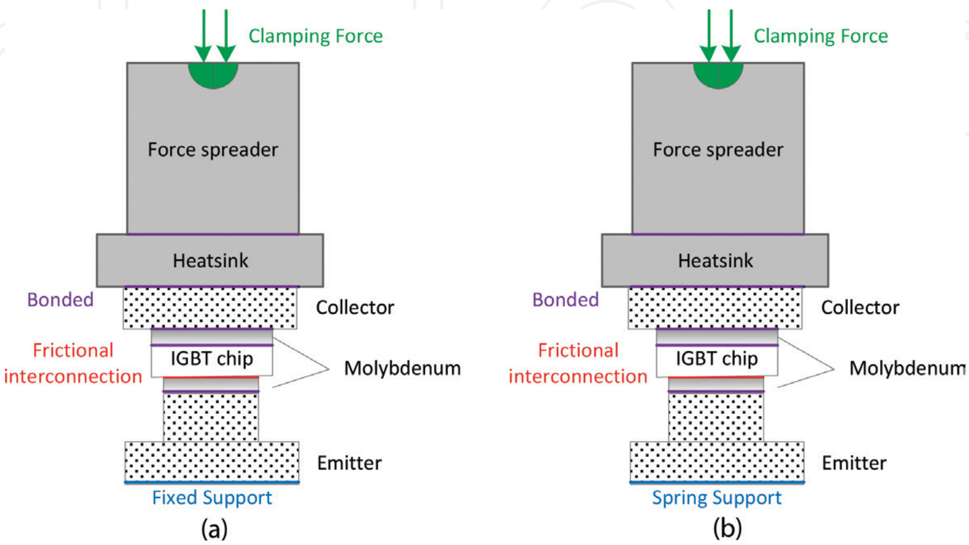

Figure 9. Simulation schematic diagram of single IGBT submodule: (a) without spring and (b) with spring.

As mentioned earlier, the rated clamping force of the single IGBT submodule is obtained through the displacement on a proper designed force spreader. The calculated clamping force of the submodule is used to compare with different conditions, and it is the real clamping force existing in the submodule after the submodule is clamped by the desired displacement.

Furthermore, the selection or the design of the disc spring is also quite important in the applications. The most important parameter for disc spring is the equivalent elastic coefficient. The higher this value, the disc spring is harder to deform which means higher force is needed to obtain the same deformation. And the lower this value, the disc spring can compensate more displacement with the same clamping force. Therefore, the selection of the equivalent elastic coefficient is a tradeoff problem. The rated clamping force of the submodule is designed to 1 kN and the displacement is 1 mm. Therefore, the rated equivalent elastic coefficient is 1e6 N/m. The submodule under the heating phase with different coefficients, range from 1e6 to 1e7, is also analyzed and the results are shown in **Table 2**.

where "without" means no disc spring is applied in the simulation and the value with a unit of N/m is the equivalent elastic coefficient of the disc spring applied in the simulation. The results show that there is no difference in the calculated clamping force of the single submodule whether a disc spring is applied or not during the clamping phase. And the calculated value is almost equal to the rated clamping force of 1 kN. That is to say, the disc spring has no influence on the clamping phase after the submodule is clamped. The disc spring is used to slow down the change rate of the clamping force during the clamping process but it will not affect the final value after the submodule is clamped. Just like the inductance in the circuit, it is used to restrict the change rate of current.

However, the clamping force will increase sharply due to the thermal stress generated by the high temperature when the silicon chip is heated up. And the value is almost 14 times of the rated clamping force. This high clamping force may mechanically damage the silicon chip. The reason is that the submodule is constricted by the clamping fixture. Thus, a disc spring is needed to compensate the displacement or deformation due to the thermal stress, and the calculated clamping force can be controlled to some extent. The increment of the clamping force is also influenced by the equivalent elastic coefficient. The calculated clamping force will be higher with a higher value of equivalent elastic coefficient. And the increment rate of 2.14, 10.65, and 21.06% is also proportional to the value of equivalent elastic coefficient. The reason is that the allowed displacement of the disc spring is 1, 0.2, and 0.1 mm with the same clamped conditions. Actually, the increment of the clamping force cannot be eliminated if the submodule is clamped even if adequate disc spring is applied. And this will not only increase the cost but also will be very difficult to obtain the desired clamping force. Therefore, the design of the disc spring should consider the requirements from application and it is a tradeoff problem.

	Clamping phase (N)		**Heating phase (N)**			
	Without	**1e6 (N/m)**	**Without**	**1e6 (N/m)**	**5e6 (N/m)**	**1e7 (N/m)**
Calculated	997.57	997.59	13,948	1021.4	1106.5	1210.6

Table 2. Calculated clamping force of the submodule comparison.

4. Internal affect factors

Those factors that mainly existed in PP IGBTs or during the design process are defined as the internal affect factors. The internal factors that may affect the clamping force distribution should be analyzed and optimized because it is quite important for the structure design of PP IGBTs. There are five parameters that may affect the clamping force distribution within PP IGBTs a lot: slim plates, thermal stress, machining accuracy, internal layout, and the design of electrodes. Among those affect factors, thermal stress is not a structure parameter that can be changed during the structure design. But this factor is quite important because it will influence the layout or the matching of silicon chips.

4.1. Slim plates

Until now, there are two main packaging styles for PP IGBTs: press pack and StakPak. The StakPak packaging style contains a spring to distribute the clamping force which is patent protected by ABB and the research is very limited. The press pack is widely used by Poseico, Fuji, Westcode, and Toshiba [20, 24]. All the researches are based on the press pack, and there are also some variations between different manufacturers. As shown in **Figure 3** and stated before, a slim plate of silver is proposed to mechanically support the single chip submodule and compensate few deformations because of its good softness.

The contribution of slim plate to the clamping force distribution within PP IGBTs is revealed with three different conditions. As it is known, it is difficult to ensure the same high of all submodules due to the machining accuracy of each component within PP IGBTs or some errors during the assembling process. Condition I is that all the submodules in PP IGBTs have the same height and condition II is that one of those submodules is 0.5 μm lower than others. Condition III is that one of those submodules is 0.5 μm higher than others. The finite element model for this simulation is also shown in **Figure 7** with nine silicon chips, and the height of chip 5 is selected to change. The clamping force distribution within the PP IGBT with different conditions is shown in **Table 3**.

No	Rated (N)	I		II		III	
		Without	With	Without	With	Without	With
1	1000	1016.9	1005.1	1043.79	1044.8	987.27	986.74
2	1000	1005.5	995.96	1043.4	1045.6	965.52	966.94
3	1000	1013.3	1000.9	1041.79	1046.3	986.31	987.55
4	1000	1004.5	976.62	1043.81	1046.1	965.52	965.9
5	1000	924.14	915.56	659.93	630.19	1200	1194.6
6	1000	1002.9	990.6	1041.46	1046.5	965.8	966.3
7	1000	1015.1	999.31	1042.57	1045.8	985.74	987.61
8	1000	1002.5	983.6	1041.03	1047.1	965.83	966.51
9	1000	1015.1	1001	1042.18	1047.7	987.52	987.39

Table 3. Clamping force distribution with different conditions.

The results show no big difference between the single submodules with applied slim plate or without. That is to say, the influence of the slim plate on the clamping force distribution can be ignored. The reason is that the deformation of the silver slim plate is very limited even it has a relative small Young's modulus.

4.2. Thermal stress

A clamping force is needed to ensure the basic functions, and all the components within PP IGBTs contact well. The silicon chips will produce much heat and increase the temperature under working condition of the PP IGBT. Thus, this high temperature induces thermal stress because all the components are constricted by the clamping fixture, and there is no space to move when they are heated up. The thermal stress during the heating phase will change the clamping force distribution within PP IGBTs to a large extent [20]. The finite element model of the conceptual PP IGBT studied consists of 44 silicon chips (30 IGBT chips and 14 FRD chips), and the chip number is marked as shown in **Figure 10**.

A finite element multi-physics model co-coupled with an electrical field, thermal field, and mechanical field is proposed to predict the clamping force distribution within the PP IGBT. The status of the clamping phase is that the PP IGBT is only clamped by the clamping fixture with a prescribed displacement. And the heating phase is the state where the clamped PP IGBT is heated up caused by the collector current to approximate its working condition. More details for this part can be found in the study [20]. The simulation results are shown in **Figure 11**.

The contact pressure distribution within the studied PP IGBT is relatively uniform under the clamping phase. However, this situation changes a lot when the PP IGBT is heated up. The pressure distribution is extremely uneven and is mainly concentrated in the center. That is to say, the clamping force distribution will also be uneven, and the change trend will be the same

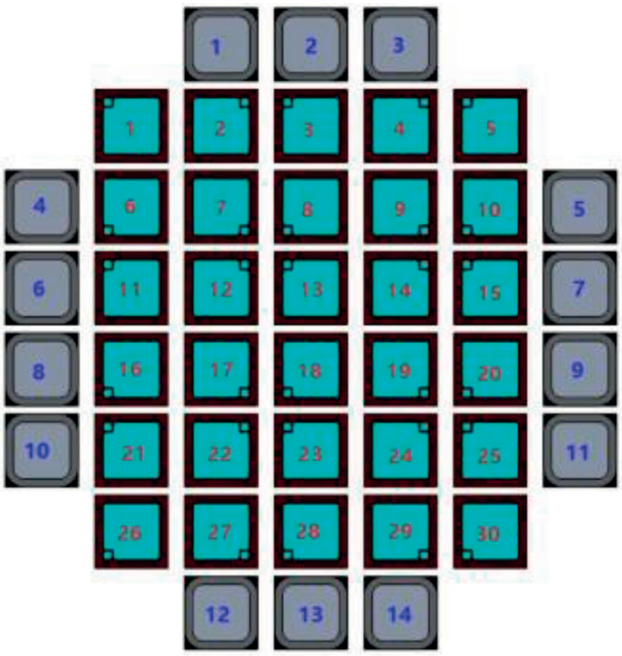

Figure 10. Internal layout and chip numbers of the conceptual PP IGBT.

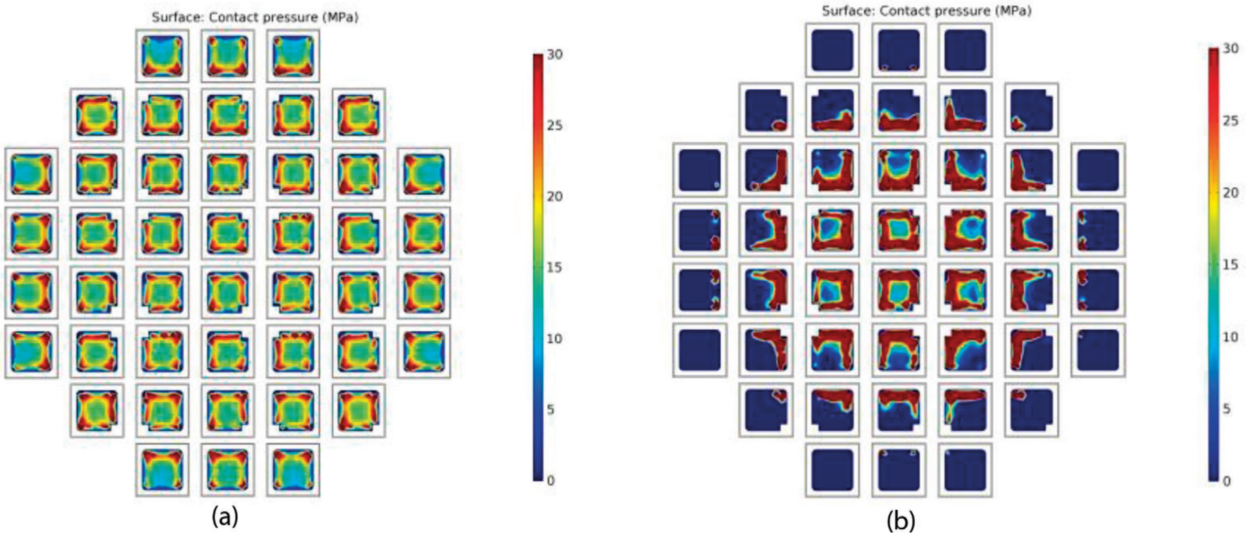

Figure 11. Contact pressure distributions within PP IGBT: (a) clamping phase and (b) heating phase.

with the contact pressure. The average clamping force of one FRD chip (#2) and three IGBT chips (#3, #8, and #13) located in the axis is extracted (marked with a red block in **Figure 10**) and compared in **Table 4**.

The reason is that the collector electrode presents a warpage when the PP IGBT is heated up, and this leads to an extremely uneven clamping force distribution. However, there also exists a little difference among the silicon chips in the clamping force distribution even in the clamping phase because of the warpage of the collector electrode. Another reason is that the pedestal is too hard to absorb the thermal stress generated by the high temperature of silicon chips. Therefore, a harder collector electrode and a softer pedestal can improve the clamping force distribution within PP IGBT.

4.3. Machining accuracy

As stated before, the PP IGBT has a multilayer structure and all components are stacked. It is impossible to control each component having the same size because of the machining accuracy. Therefore, the difference or error in the size among components is inevitable. Furthermore, the size error existing in each component will also be summed up during the assembling process as the components are stacked. Adding up all factors means that the height of each submodule will not be the same. These existing differences of the height of the submodules will affect the clamping force distribution. The finite element model including 11 IGBT chips and five FRD chips is shown in **Figure 12**. More details can be found in the study [13].

The FRD chip 5 with different height tolerances, ranges from 0 to −3 μm, is selected to predict the clamping force distribution within the studied PP IGBT. The von Mises stress on the surface of the silicon chips (IGBT 4, IGBT 8, FRD2, and FRD5) with different heights is extracted and shown in **Figure 13**. Furthermore, the average clamping force of FRD chip 5 is extracted under different height tolerances as shown in **Figure 14**.

The results show that the clamping force of FRD chip 5 decreases sharply while the height tolerances is increasing. The clamping force decreases to less than 100 N, which is much less than

Chip no.	Rated (N)	F (N)		Deviation (%)	
		Case 1	Case 2	Case 1	Case 2
#2	1660	1596.3	84.841	−3.84	−94.89
#3	1558	1549.2	2301.3	−0.56	47.71
#8	1558	1569.1	2949.6	0.71	89.32
#13	1558	1577.8	3072.5	1.27	97.21

Table 4. Average clamping force comparison.

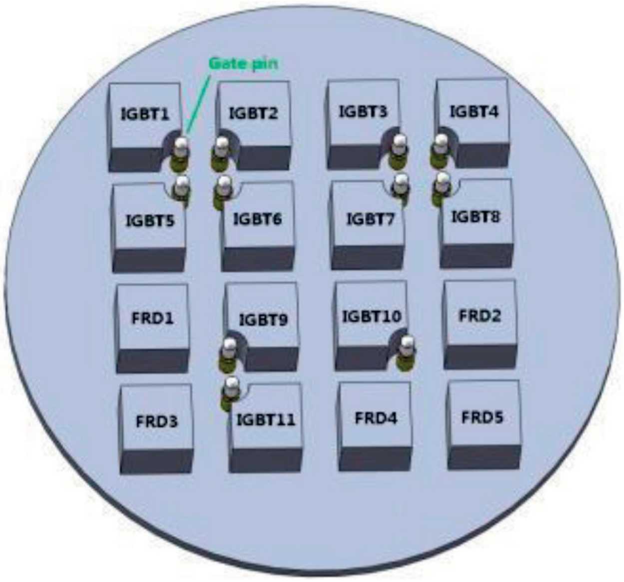

Figure 12. Finite element model and chip number.

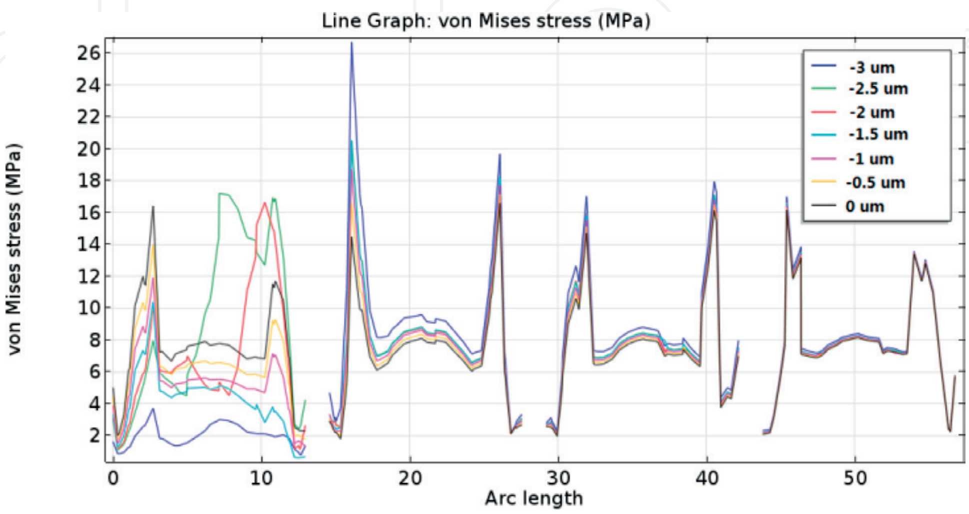

Figure 13. von Mises distribution of the selected silicon chips.

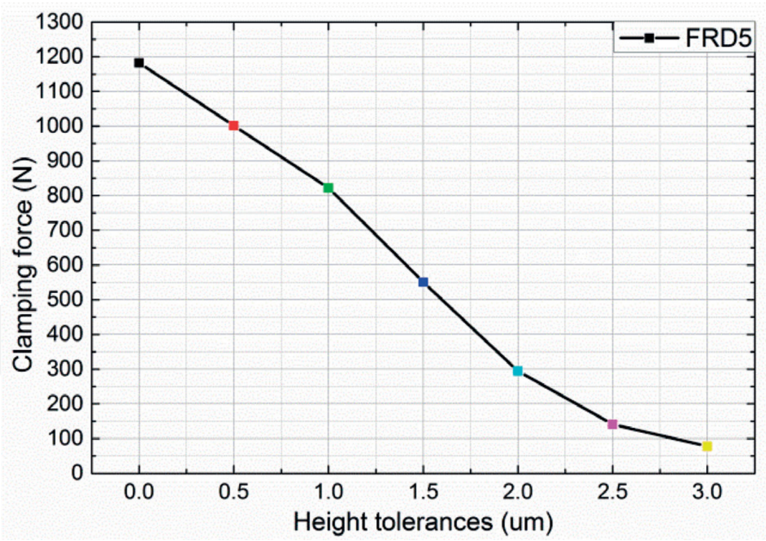

Figure 14. Clamping force of FRD chip 5 under difference height tolerances.

the rated clamping force, when the height tolerance is 3 μm. It is assumed that this chip will lose contact if the height tolerance is more than 3 μm. Meanwhile, the von Mises of the chip nearby the FRD chip 5 will increase sharply, especially the von Mises in the border between the active area and the terminal area. This area is very easy to crack if too much clamping force is applied as stated in [20]. Therefore, the machining accuracy should be controlled to a certain extent to ensure the clamping force distribution. The maximum height tolerance of each submodule should be controlled within 3 μm based on this simulation result.

4.4. Internal layout

From the simulation results of the study [13, 20], there still exists some difference among the submodules in the clamping force distribution within PP IGBTs because of the warpage of the collector electrode even everything is well controlled. The influence of the electrode on the clamping force in this packaging style is inevitable. However, the internal layout can be changed to reduce the influence of the electrode and improve the distribution a little bit. Three layouts are designed and analyzed through the finite element model as shown in **Figure 15**.

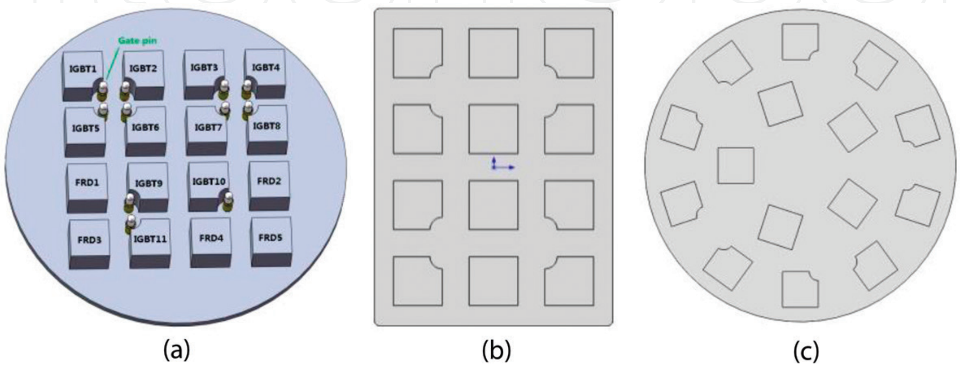

Figure 15. Three different layouts: (a) circular electrodes with the square internal layout, (b) square electrodes with the square internal layout, and (c) circular electrodes with the circular internal layout.

Proposal I is the circular electrodes with the square internal layout; proposal II is the square electrodes with the square internal layout, and proposal III is the circular electrodes with the circular internal layout. The different internal layouts lead to some distinction in the warpage of the electrodes and then affect the clamping force distribution. The average clamping force of each silicon chip is extracted and listed in **Table 5**.

From the clamping force distribution of three different internal layouts, it is shown that it is relatively uniform and the error is acceptable. Considering the difference between the IGBT chips and FRD chips, proposal II is better than I and III with a relatively lower error between the IGBT chips and FRD chips of 4.3% (2.65% to (−1.65%)). The error of those two proposals is 14.98 and 15.75%, respectively. Considering the difference among IGBT chips or FRD chips, proposal III is better because all the IGBT chips or FRD chips are located in the same circular and have the same deformation. However, the error among IGBT chips or FRD chips of proposal II is also relatively low with a value of 0.9 and 0.39%, respectively. In conclusion, proposal II is better than those two proposals because the electrode undergoes little deformation when the PP IGBT is clamped.

4.5. Design of electrodes

Many factors that affect the clamping force distribution within PP IGBTs have been analyzed before because it is known that most of those factors lead to warping the electrode. Therefore, the design of the collector electrode is also quite important for the clamping force distribution

No	Rated (N)	Average clamping force (N)			Error (%)		
		I	II	III	I	II	III
IGBT1	1129	1172.5	1119.2	1068.9	3.85	−0.87	−5.32
IGBT2	1129	1179.3	1111.9	1069.5	4.46	−1.51	−5.27
IGBT3	1129	1176.5	1111.2	1069.6	4.21	−1.58	−5.26
IGBT4	1129	1168.1	1119.8	1069.5	3.46	−0.81	−5.27
IGBT5	1129	1168.1	1120.0	1069.6	3.46	−0.80	−5.26
IGBT6	1129	1026.2	1110.8	1068.5	−9.11	−1.61	−5.36
IGBT7	1129	1024.6	1110.4	1069.5	−9.25	−1.65	−5.27
IGBT8	1129	1162.5	1120.5	1070.0	2.97	−0.75	−5.23
IGBT9	1129	1010.3	—	1069.3	−10.5	—	−5.29
IGBT10	1129	1004.9	—	1070.0	−11.0	—	−5.23
IGBT11	1129	1136.6	—	—	0.67	—	—
FRD1	1161	1207.2	1191.8	1281.1	3.98	2.65	10.39
FRD2	1161	1198.9	1186.1	1281.6	3.26	2.16	10.36
FRD3	1161	1189.9	1187.2	1281.3	2.49	2.26	10.35
FRD4	1161	1192.3	1190.8	1281.2	2.70	2.57	10.28
FRD5	1161	1182.1	—	1280.3	1.82	—	10.34

Table 5. Average clamping force comparison for different internal layouts.

of PP IGBTs. A step has to be designed in the electrode to form a flange to make the PP IGBT a confined space to protect the silicon chips out of environment disruption. Two important parameters in this part are shown in **Figure 16** and are explained.

Where A is the diameter of the electrode and B is the equivalent diameter of the pedestals. The parameter A is the most important parameter because it is used to conduct the current, heat flux, and the clamping force. And furthermore, the equivalent diameter B is also very important that the clamping force is transmitted through the pedestals. Whether the value of A is matched with B or not will affect the clamping force to a large extent. The finite element model used in this section consists of 40 IGBT chips and 20 FRD chips, and this model is axial symmetry. Only half of this model is simulated to save time, and then the results can be expanded to the whole model. Firstly, the electrode diameter of 125 and 141 mm is simulated and the pressure on the surface of the silicon chips is shown in **Figure 17**.

Where the value of 125 mm is smaller than the equivalent diameter of pedestals and 141 mm is larger than that value. The simulation results show that the pressure will concentrate in the center of the PP IGBT when the diameter of the electrode is smaller than the equivalent diameter of pedestals. And the pressure will concentrate in the boundary of the PP IGBT when the diameter of the electrode is too large. The reason is that the electrode undergoes a different direction warpage under those two conditions. Then, different electrode diameters as 125, 127, 131, 135, 139, and 141 mm are simulated based on this finite element model and the average clamping force of each silicon chip is extracted. The clamping force error of each silicon chip is shown in **Table 6** with half model.

As it is seen in the results, the majority of the IGBT chips have plus deviation/error when the electrode diameter is smaller than 135 mm and they have minus error when the diameter is

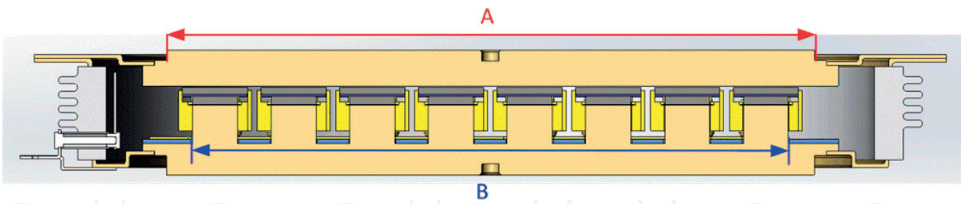

Figure 16. Explanation for important parameters.

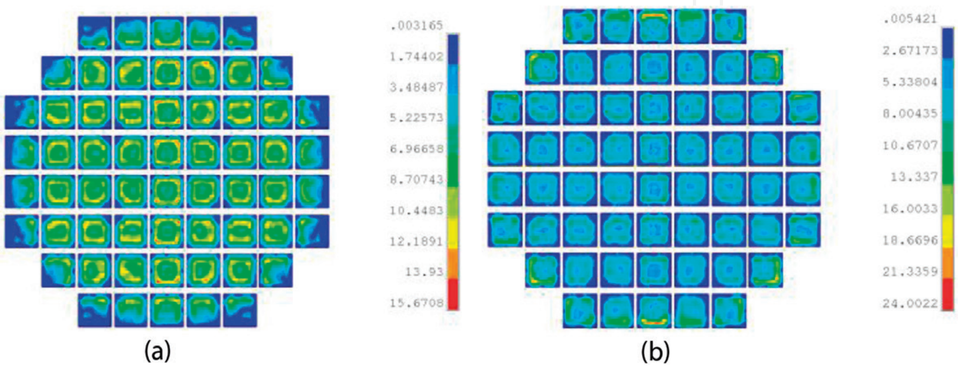

Figure 17. Pressure distribution on the surface of the silicon chips: (a) diameter of 125 mm and (b) diameter of 141 mm.

No.	⌀125		⌀127		⌀131		⌀135		⌀139		⌀141	
	IGBT	FRD	IGBT	FRD	IGBT	FRD	IGBT	FRD	IGBT	FRD	IGBT	FRD
1	−29.35	−61.44	−23.56	−54.53	−13.34	−39.45	−4.96	−22.76	3.02	−5.98	6.90	2.48
2	18.23	−25.75	5.32	−17.95	10.10	−4.35	4.72	7.32	−0.76	18.08	−3.77	23.50
3	1.95	−60.66	18.26	−53.91	0.30	−38.15	3.15	−21.07	−3.60	−3.90	−7.18	4.52
4	7.81	−6.15	5.60	−2.10	9.43	.53	3.78	3.35	−1.03	21.04	−3.98	24.58
5	3.52	3.25	8.91	18.72	11.60	1.56	4.26	3.51	−3.47	−3.64	−6.72	−7.57
6	2.41	2.64	18.32	18.72	11.10	0.87	3.65	3.61	−3.73	−3.27	−7.17	−6.39
7	−20.50	20.15	−15.20	16.31	−5.59	.14	2.01	2.32	9.24	−3.83	12.96	−6.66
8	0.83	−61.04	7.46	−54.13	9.45	−38.38	2.08	−20.88	−5.34	−3.91	−9.37	4.53
9	2.74	−25.16	18.85	−17.34	0.83	−3.87	3.77	7.03	−3.84	17.74	−7.15	24.17
10	0.17	−61.03	6.52	−54.72	.57	−39.33	2.50	−22.88	−3.74	−5.71	−7.00	2.25
11	−20.57		−15.12		−5.31		2.30		9.16		12.99	
12	2.39		18.40		9.92		2.74		−5.08		−8.88	
13	22.78		18.83		0.91		3.47		−4.29		−6.82	
14	20.28		16.52		9.37		2.59		−3.68		−7.20	
15	7.19		14.59		9.10		3.30		−1.22		−4.86	
16	22.83		18.95		11.58		4.51		−3.27		−6.88	
17	21.72		17.74		10.71		3.36		−4.00		−7.42	
18	7.49		15.27		9.80		5.07		−0.34		−4.02	
19	2.73		8.53		10.05		2.78		−3.67		−6.89	
20	−29.45		−23.26		−13.14		−4.63		3.02		7.08	

Table 6. Average clamping force errors among silicon chips with half model (unit: %).

larger than 135 mm. And the clamping force distribution among IGBT chips is uniform. For FRD chips, there exists some difference among those chips but this is acceptable. Therefore, the electrode diameter of 135 mm is the best among those diameters, and this value is close to the equivalent diameter of pedestals. That is to say, the best way to improve the clamping force distribution within PP IGBTs is to match the electrode diameter with the equivalent diameter of pedestals during the electrode design process.

5. Conclusions

The clamping force distribution within PP IGBTs is quite important because it affects not only the electrical and thermal characteristic but also the reliability. Many factors may affect the clamping force that has been classified and analyzed through the finite element method in this chapter, and the simulation results are well presented and explained. Based on the simulation results, we know that we should pay more attention to the thermal stress, machining accuracy, internal layout, and electrode design during the structure design process, especially the thermal stress. The disc spring is very important for the PP IGBT application, and this factor also should be considered during the mechanical simulation. The slim plate can be omitted in the mechanical simulation that it is too thin and its contribution to the clamping force distribution is very limited.

The clear classification and analysis of all the factors that affect the clamping force distribution can give a guideline not only for the semiconductor manufacturers to optimize the structure design but also for users to take full advantages of the PP IGBTs.

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