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Keywords

≪Conduction losses≫, ≪IGBT≫, ≪Modelling≫, ≪Switching losses≫, ≪Thermal stress≫

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Abstract

Life time prediction and thermal management are among the key issues regarding the performance of today's semiconductor devices. And a fast and accurate thermal model can be used to tackle those problems more efficiently. In this paper, different thermal models of an IGBT power module have been established and compared. Firstly, a 3D finite element method (FEM) model is simulated in COMSOL. And then, a lumped parameter thermal model with considering different aspects (heat spreading and thermal coupling) is derived. The simulation indicates that the proposed model can achieve a relatively accurate result within a short simulation time.

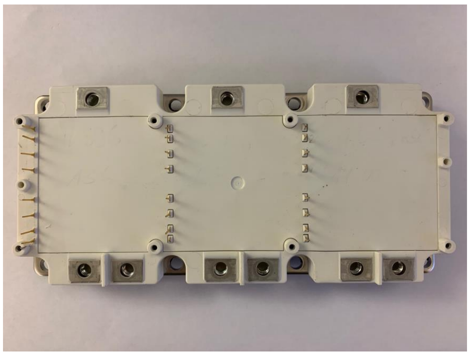
Introduction

Nowdays, power converters are widely used in various electric power applications. The role of converting energy between different sources has made the power converter a vital part in the electrical system. For some of the applications, such as electrical vehicles, the key component of a power converter is the semiconductor module, or the IGBT module in this paper. One of the issues coming along with the large scale use of IGBT modules is the reliability. In addition, the compact area and high power density design of the new generation semiconductor modules brings more challenge to the reliability. In [1], different failure mechanisms occurring in modern IGBT power modules have been reviewed. And it is found that bond wires, the solders between different layers are mostly responsible for these failures. In [2], it is reported that more than half of the failures of IGBT modules are related to the cyclical thermal stress. In that sense, the thermal behaviors of IGBT modules are crucial to the reliability issue. Therefore, an accurate thermal model will facilitate the thermal design of IGBT modules. Moreover, a reduced failure rate in the modules, means a decrease of total converter cost.

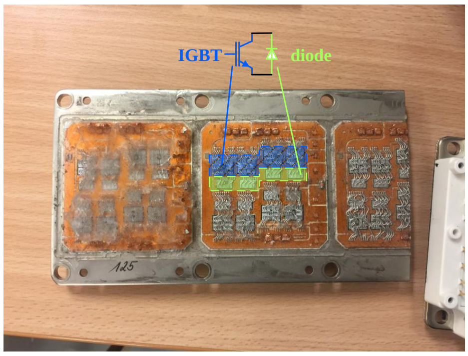
The equivalent thermal models of IGBT modules are usually described in a manufacturers' application notes, such in [3] and [4]. However, these offered models usually have some assumptions which are only for ideal cases. Some research has been done to mitigate the flaws in those models. In [5] and [6], thermal models with heat spreading angle are proposed, however they do not consider the thermal coupling effect of adjacent semiconductor chips. In [7] and [8], thermal coupling effect has been considered in developing lumped parameter thermal models. However, the temperature variants in different layers could not be simulated in their thermal models. Accordingly, the purpose of this paper is to propose a fast and accurate thermal model, which can be used to predict the temperature in some of the key layers in IGBT modules.

The investigated IGBT module and conditions

The IGBT power module ($FS600R07A2E3$) which has been investigated in this paper is a commercial product from Infineon, and is shown in Fig. 1a. The IGBT module integrates the power electronic semiconductors within one case; and it allows the dissipated heat from the semiconductors chip to transfer to the pin-fin structure cooling plate. The inside of the investigated IGBT module is shown in Fig. 1b. It can be seen that for each IGBT/diode pair, to meet the high current requirement (600 A), four silicon chips are mounted on the direct bond copper (DBC) layer in parallel.



(a) FS600R07A2E3

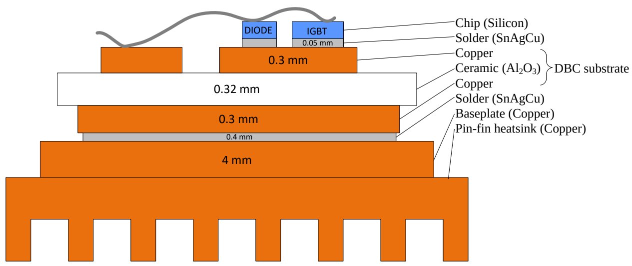


(b) Inner picture of FS600R07A2E3

Fig. 1: Typical figure of the investigated IGBT module FS600R07A2E3 [9]

Currently, the technique of using DBC as insulation and heat conductor for IGBT modules is commonly used [4]. The power semiconductors are soldered on top of the DBC, while an integrated cooling plate is placed underneath the DBC. The picture of the cross section of the studied IGBT module is shown in Fig. 2a. It can be seen that different layers are stacked together on top of a pin-fin structure cooling plate. A more detailed cross section figure of the IGBT module is illustrated in Fig. 2b. And the properties of different layers for the studied IGBT module is shown in Table I.

(a) Cross section of the IGBT module



(b) Layer stack of the IGBT module

Fig. 2: Corss section of the investigated IGBT module

Table I: characteristics of different layers for the investigated IGBT module

Layer	Material	Density (kg/m^3)	Thermal conductivity ($W/(m \cdot K)$)	Specific heat capacity ($J/(kg \cdot K)$)
Die	Silicon	2329	130	700
Solder joints	SnAgCu	7370	68	220
DBC ceramic	Al_2O_3	3965	35	730
Copper	Cu	8960	400	385

Thermal models

A lumped parameter thermal model is generally represented by a equivalent circuit. The equivalent circuit consists of a heat source and several transient thermal impedance. It can be used to model the transient thermal behaviour of an IGBT power module. The transient thermal impedance Z_{th} can be quantified with different thermal resistances and capacitance, and is determined by

$$Z_{th} = \frac{T_j - T_a}{P}, \tag{1}$$

where T_j is the junction temperature of power semiconductors, T_c is temperature of the case, P is the losses disspated from semiconductor chips.

One commonly used equivalent circuit model is the Cauer model, which is given in Fig. 3a. This model contains several RC ladders; and each RC ladder represents one layer of the stacked power semiconductors module. Another equivalent circuit model representation is the Foster model, which is given in Fig. 3b. It should be mentioned that the different RC networks in this model have no physical meaning, so the RC values are typically acquired by fitting the transient temperature curve from a datasheet.

(a) Cauer model

(b) Foster model

Fig. 3: Different equivalent circuit thermal models

IGBT module loss determination

Power P in Fig. 3a and Fig. 3b is the power dissipation of IGBT module. It consists of two parts, one is the conduction loss P_{con} and the other one is the switching loss P_{sw}. In reality, it is one signal $p(t) = u(t) \cdot i(t)$, however, in common calculation procedure, they are split into two components. Both of the two loss components are related to the characteristics of power semiconductors, power ratings and operation temperature.

One way to determine the losses is the calculation method presented in [10], which means that based on the data offered by a manufacture, the losses can be calculated.

P_{con} of the IGBT and the diode can be determined by,

$$P_{con\_IGBT} = \left(\frac{1}{2\pi} + \frac{M\cos\varphi}{8}\right)V_{CE0}\hat{I} + \frac{1}{8} + \frac{M\cos\varphi}{3\pi} r_{CE}\hat{I}^2 \tag{2}$$

$$P_{con\_D} = (\frac{1}{2\pi} - \frac{M\cos\varphi}{8})V_{F0}\hat{I} + \frac{1}{8} + \frac{M\cos\varphi}{3\pi}r_F\hat{I}^2 \quad (3)$$

where M is the modulation index, $\cos\varphi$ is the power factor, V_{CE0} is the IGBT forward voltage, V_{F0} is the diode forward voltage, r_{CE} is the IGBT on resistance, r_F is the diode on resistance and $\hat{I}$ is the peak value of the output current.

P_{sw} of the IGBT and diode can be calculated by,

$$P_{sw} = f_{sw}E_{sw}(\frac{1}{\pi} \cdot \frac{\hat{I}}{I_{ref}})^{K_i} \cdot (\frac{V_{cc}}{V_{ref}})^{K_v} \quad (4)$$

where f_{sw} is the switching frequency, E_{sw} is the loss of a reference switching action, I_{ref} is the reference current for the calculation, V_{ref} is the reference current for the calculation, V_{cc} is the supply voltage, K_i is the exponent of current dependency and K_v is the exponent of voltage dependency.

The splitting of the loss into two components facilitate the implementation in a simulation tool, such as PLECS. By inserting a series of data points from the datasheet to create look-up tables in the PLECS model, the losses of the IGBT module can be simulated. The calculated power losses and simulated power losses under different reference voltages are compared in Table II.

Table II: Power dissipation results of the investigated IGBT module with using different methods

	I_{ref} = 400 A, V_{ref} = 300 V, T_{ref} = 125 °C, $\cos\varphi$=0.866, M=0.866, f_{sw}=10 kHz			I_{ref} = 400 A, V_{ref} = 400 V, T_{ref} = 125 °C, $\cos\varphi$=0.866, M=0.866, f_{sw}=10 kHz		
	Matlab	Formula	PLECS	Matlab	Formula	PLECS
IGBT switching loss [W]	23.62	23.57	23.63	46.45	46.34	46.68
IGBT conduction loss [W]	21.59	21.63	21.45	30.45	30.51	30.30
Diode switching loss [W]	5.74	5.79	5.99	9.09	9.17	9.50
Diode conduction loss [W]	7.32	7.29	7.20	9.98	9.94	9.84

COMSOL modelling

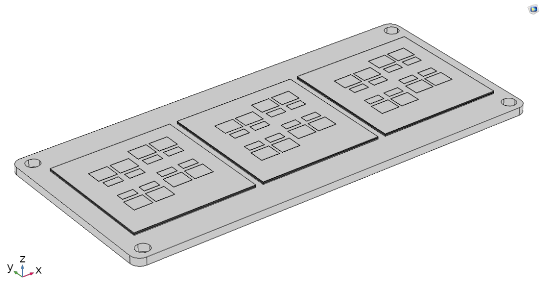
Based on the measured geometry and the layer characteristics listed in Table I, a FEM simulation model is built in COMSOL. To simplify and reduce the simulation process, instead of employing multiphysics simulation, an equivalent heat transfer coefficient of the baseplate is used to represent the liquid cooling effect. The heat transfer coefficient is set to a value so that the same junction temperature in the simulation and in the datasheet. The baseplate is assumed to be mounted on a cooling plate with a fixed temperature of 25 °C. The ambient temperature is set to 20 °C.

The geometry and mesh properties of the IGBT module are shown in Fig. 4. As the foucs of this simulation is on the semiconductor chips, a manual refined mesh is applied, which means that the different layers have been applied with different mesh settings.

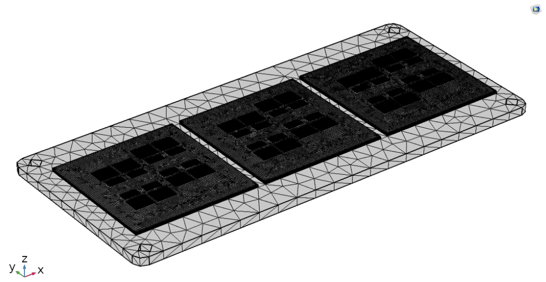
The acquired losses of the IGBT and diode from Table II can be set as the heat source for corresponding blocks in COMSOL. In this simulation, the PLECS simulation results under V_{ref} = 400 V are selected, which means that the IGBT loss is set to be 45.08 W and the diode loss is set to be 13.19 W. The COMSOL simulation result is shown in Fig. 5.

A multilayer 2D thermal model with considering heat spreading effect

From [1], it is reported that the bond wires, the solder under the silicon chips and the solder under DBC have the highest probability to breakdown due to cyclic thermal stressing. Thus it is of high interest to see how the temperature inside these layers vary with time. As shown in the COMSOL modelling section, a detailed 3D FEM model can be used to simulate the steady state temperature of these layers.

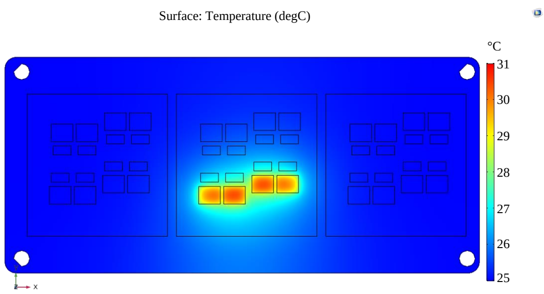


(a) COMSOL geometry

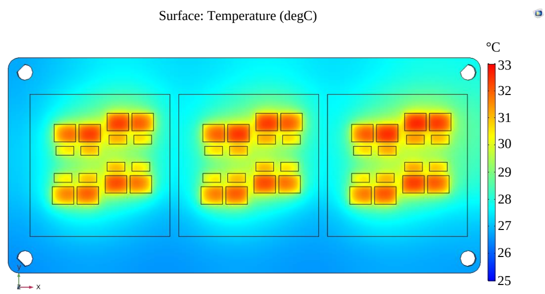


(b) Vie of mesh

Fig. 4: Geometry and mesh view of the IGBT module built in COMSOL



(a) Only losses in one IGBT



(b) Losses in all IGBT/diode chips

Fig. 5: Temperature distribution of COMSOL simulation

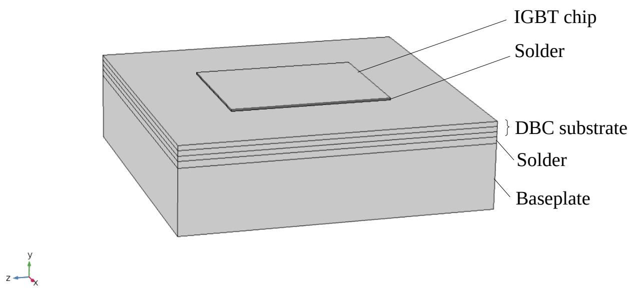
However, the transient temperature response in the FEM simulation will be computationally heavy if it has to be calculated for each time point. Therefore, even though the FEM model has the advantage of high accuracy, it is not suitable for long term thermal analysis, such as life time estimation of IGBT modules. Another way to do this is to use a Cauer model which has different RC ladders to represent the different layers. From Fig. 5, it can be seen that the IGBT and diode chips inside the module has a symmetric geometry, thus, to decrease the FEM simulation complexity, a FEM model of an IGBT chip with the equivalent substrate and baseplate underneath has been built in COMSOL, which is shown in Fig. 6a. The Cauer impedance network with the different physical layers of one IGBT chip is shown in Fig. 6b.

The COMSOL simulation result of this small IGBT chip block is shown in Fig. 7a. An interesting thing can be seen is that the heat flux (red arrows in Fig. 7a) has a spreading effect when flowing from the IGBT chip to the DBC substrate. This phenomenon can be illustrated by a simple model in Fig. 7b, where the angle ϕ is the effective heat spreading angle [12]. Thus, a heat spreading angle need to be considered when using the 2D thermal impedance network to calculate the temperature response.

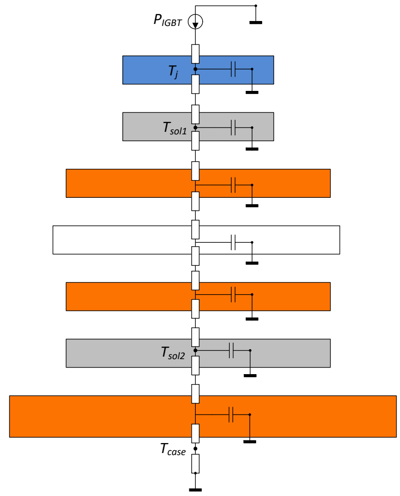
In practice, an heat spreading angle of 40° can be added in order to represent the heat spreading effect. However, it should be noted that this only applies for the condition when the heat propagation is not obstructed by subsequent layers with low heat conductivity [11]. In this simulation, in order to let the PLECS simulation result match with the FEM simulation result, an angle of 32.5° is selected. And the simulation results between COMSOL FEM model and PLECS Cauer model are compared in Fig. 8. It can be seen that the PLECS Cauer model simulation results are really close to COMSOL results.

A multilayer 2D thermal model with considering thermal coupling effect

The above thermal model only considers the self-heating of the devices caused by the single operational semiconductor chips. However, when two semiconductor chips are placed close to each other, especially for those compact modules, the thermal coupling effect between the IGBT and diode can heat up the

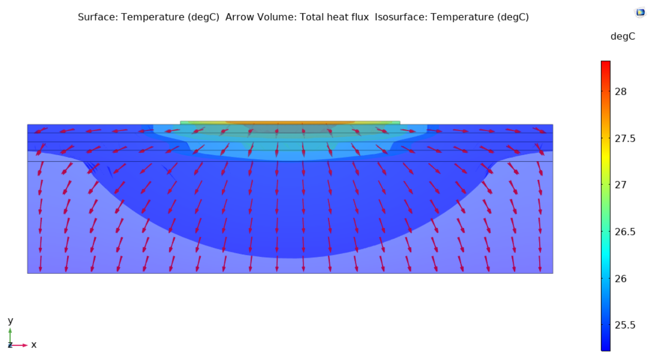


(a) IGBT chip with euqivalent area of substrate and baseplate

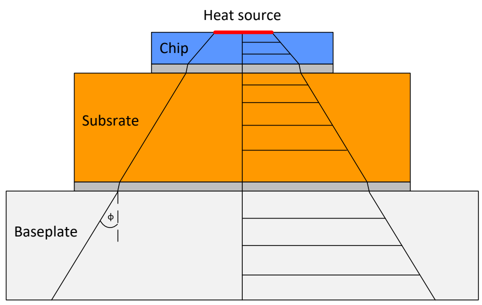


(b) A 2D Cauer thermal impedance network of one IGBT chip

Fig. 6: Single IGBT chip and Cauer impedance network



(a) One IGBT chip COMSOL simulation result



(b) Simple heat spreading model of layered structure

Fig. 7: Heat spreading in multilayer structure

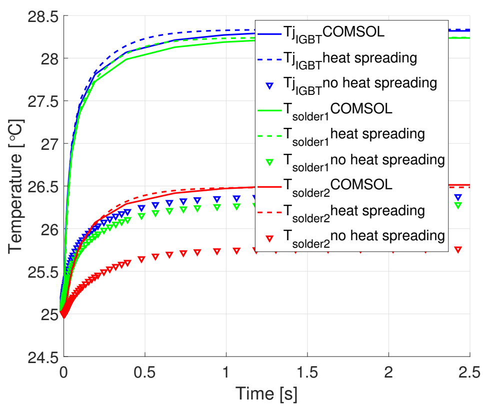
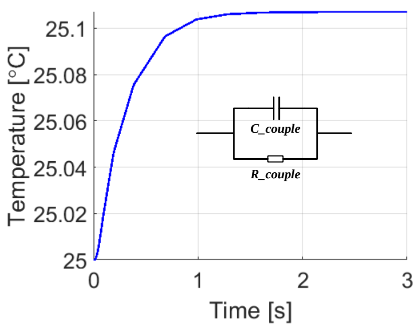


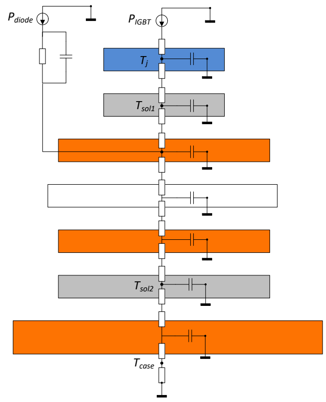
Fig. 8: Simulation results comparison with considering heat spreading effect

devices to a higher temperature. The distance between the IGBT chip and diode chip is around 1.87 mm, and based on [4], when the distance between two chips is less than 3 mm, the thermal coupling effect should be considered. On the other hand, from the COMSOL simulation result which is shown in Fig. 5a, it can be seen that when one IGBT (four semiconductor chips in parallel) is heated, the temperatures of the anti-parallel diodes which are next to the IGBT chips rise as well. In that sense, for this multi-chip IGBT module, the thermal coupling effects should be considered.

Similar as in previous section, a small block with only considering one IGBT chip and one diode chip can be built to represent the whole module in order to reduce the simulation time. And the coupling thermal impedance from the diode to the IGBT can be acquired by using (1). When a heat source is applied on the diode chip, the temperature inside the IGBT chip will rise with time. And in COMSOL, this temperature response can be observed, which is shown in Fig. 9a. It can be seen that the temperature response has the characteristic of an exponential curve, which means that one Foster RC link can represent the dynamic behavior of this curve. By using the curve fitting tool in MATLAB, the values of R and C in the Foster RC link can be acquired. And the simulation result of temperatures in different layers when considering the thermal coupling effect is shown in Fig. 10. It can be seen that with adding thermal coupling effect, the FEM simulation result and PLECS simulation result have a small difference between each other. This is due to the thermal coupling term changes the heat flux distribution inside the substrate layers, and the previous fixed 32.5° does not completely represent the current condition. However, the difference between these two simulation results are acceptable, which means that this modified thermal model can be used for future long term analysis.



(a) Temperature response in the IGBT chip



(b) Modified 2D thermal model

Fig. 9: Thermal model modification due to thermal coupling

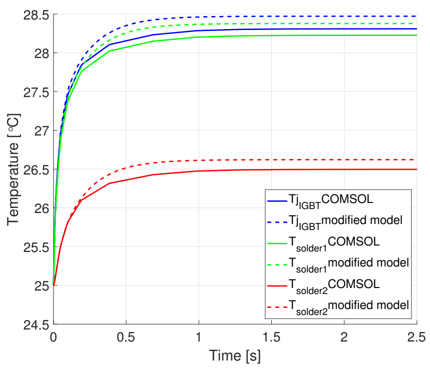


Fig. 10: Simulation results comparison with considering thermal coupling effect

Conclusion

In this paper, a Cauer thermal model which can be used to represent the thermal behaviors of an IGBT power module are developed through FEM simulations. And by considering different aspects (heat spreading and thermal coupling), it is found that the proposed thermal model can achieve a relative accurate simulation result within a short simulation time. And this model can be used for long time analysis in the future.

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