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Thermal analysis of the half-bridge IGBT power module with analytical, numerical and experimental methods

Abstract. *This paper describes a thermal analysis of the half-bridge IGBT power module, which is mounted to the heat sink. Power dissipation of semiconductor devices gradually heats the power module up to the certain temperature. The main objective of this research is to calculate and verify the temperature rise of the system for different cases of power dissipation and forced cooling conditions. Temperature rise in the case when power dissipation achieves its maximum can be predicted. Several solutions are proposed: analytical, numerical (finite element methods) and experimental.*

Streszczenie. *Artykuł opisuje analizę cieplną półmostkowych modułów mocy IGBT zamontowanych do urządzeń grzejnych. Dyssypacja mocy urządzeń półprzewodnikowych stopniowo nagrzewa moduł mocy do pewnej temperatury. Głównym Selene tych badań jest obliczenie i weryfikacja wzrostu temperatury różnych systemów dyssypacji energii i wymuszonych warunków chłodzenia. Wzrost temperatury w przypadku kiedy dyssypacja energii osiąga maksimum może być przewidziany. Zaproponowano analityczne i numeryczne rozwiązania problemu.* (***Analiza cieplna półmostkowego modułu mocy IGBT metodami analitycznymi, numerycznymi i doświadczalnymi***)

Keywords: finite element methods, heat equation, thermal analysis, power module.
Słowa kluczowe: metoda elementów skończonych, równanie cieplne, analiza termiczna, moduł mocy

Introduction to the power module

This paper describes a thermal analysis of the half-bridge IGBT power module. Power modules are widely used in all branches of industry. They are usually fixed to the heat sink, which provides the better cooling of the device. Heat sink is often made of aluminium and it is attached to the bottom side of the power module. The structure of the IGBT module and the material layer structure are shown in Fig. 1. It is actually a half-bridge module, which contains two IGBT transistors and two hybrid diodes. The diode and transistor chips are soldered to the isolation substrate, in this case aluminium oxide Al_2O_3 [1], [2]. Isolation substrate has a metalized surface (copper). The chips and the isolation substrate are electrically isolated from the module base plate. This particular power module is made upon Direct Copper Bonding (DCB) technology. Thickness of the diode and transistor silicon chips is approximately 360 μm, substrate is approximately 700 μm thick and copper base plate is 3 mm thick [1], [2].

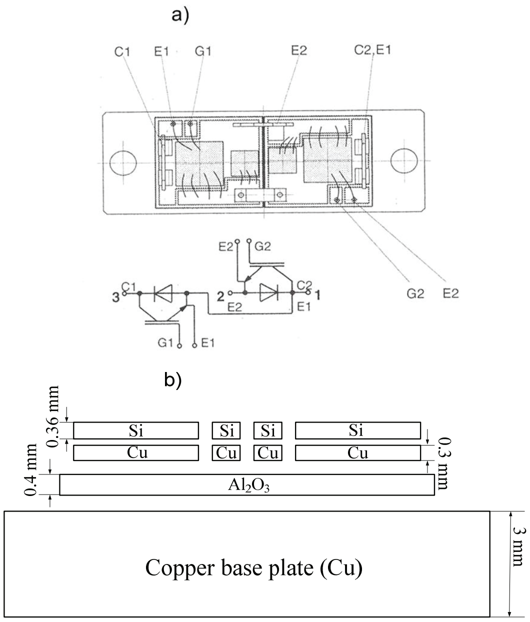

Fig. 1. a) Structure of the IGBT power module b) Vertical section; layer structure of the IGBT power module

Interconnections between the individual semiconductor devices consist of alloyed aluminium bond wires. The wire is attached at both ends using a combination of heat, pressure, and ultrasonic energy to make a weld. In this particular case, bond wires are attached with wedge bonding. The power module housing is made of a thermoplastic material with excellent thermal properties. The housing enables the proper temperature distribution on the upper side of the module.

Heat equation and thermal analysis

Heat conduction equation [3] is a partial differential equation, which is explicitly given as (1):

$$\frac{\partial U(x,y,z,t)}{\partial t} = k\nabla^2 U(x,y,z,t) \tag{1}$$

where U is temperature function and k represents thermal diffusivity of the material. Variation in temperature, respectively, heat distribution in the given 3D Cartesian region, with coordinates x, y, z, can be described with the general heat equation (1). In general, there are different sources for heating. The most common source for heating of the electric drives is Joule losses. In this particular case, Joule losses are caused by switching or conducting of the semiconductor devices (IGBTs and power diodes). Mentioned Joule losses are applied to the thermal numerical model as heat sources and therefore, the thermal analysis is completely adjusted to the real situation.

Temperature distribution throughout the power module has been calculated with general heat equation (1). The 3D Cartesian coordinate system (or any other 3D coordinate system) requires the solution with derivative to the given coordinates, including the derivative with respect to time. However, if the initial presumption is that temperature changes only along the x axis, the general heat equation (1) takes the following form (2):

$$\frac{\partial U(x,t)}{\partial t} = k\frac{\partial^2 U(x,t)}{\partial x^2}. \tag{2}$$

The temperature function can be divided into two independent functions (3):

(3) $$U(x,t)=X(x)\cdot T(t)$$

where function $X(x)$ only depends on the position and function $T(t)$ only varies with time [3]. With separation of variables, the heat equation (2) is transformed as (4):

(4) $$\frac{\partial(X(x)\cdot T(t))}{\partial t}=k\frac{\partial^2(X(x)\cdot T(t))}{\partial x^2}\rightarrow$$
$$X(x)\frac{\partial T(t)}{\partial t}=kT(t)\frac{\partial^2 X(x)}{\partial x^2}.$$

The final heat equation is given by (5):

(5) $$\frac{1}{kT(t)}\frac{\partial T(t)}{\partial t}=\frac{1}{X(x)}\frac{\partial^2 X(x)}{\partial x^2}=-\frac{1}{\lambda^2}$$

where both sides must be equal to a constant, in this case $-1/\lambda^2$. The solution for the time variable function $T(t)$ is exponential and the position function $X(x)$ has a trigonometric solution. The constant contains a negative sign to assure that the exponential solution remains finite in all cases. The solutions are given by (6):

(6) $$T(t)=Ae^{-\frac{k\cdot t}{\lambda^2}},\ X(x)=B\cos\left(\frac{x}{\lambda}\right)+C\sin\left(\frac{x}{\lambda}\right)$$

where A, B and C represent constants and k is thermal diffusivity of the material. The set of boundary conditions, which describe the physical problem, is (7):

(7) $$U(x,0)=U_0,\ \frac{\partial U(D,t)}{\partial t}=0,\ U(0,t_{\mathrm{f}})=U_{\mathrm{f}}$$

where U_0 is the initial value of the temperature, t_{f} is the period of time during which the system achieves the steady state (it is supposed to be infinite), D is the physical length of the analyzed problem and U_{f} represents the final temperature value, respectively. After the infinite period of time t_{f}, temperature achieves a final value U_{f}, which depends on the position only and it can be expressed with (8):

(8) $$U_{\mathrm{f}}(x)=U_0\frac{e^{-\frac{k\cdot t_{\mathrm{f}}}{\lambda^2}}\cdot\sin\left(\frac{D}{\lambda}\right)}{\sin\left(\frac{x}{\lambda}\right)\cdot\left(1-\cos\left(\frac{D}{\lambda}\right)\right)},$$
$$t_{\mathrm{f}}\rightarrow\infty\Rightarrow$$
$$U_{\mathrm{f}}(x)=U_0\sqrt{\frac{1+\cos\left(\frac{D}{\lambda}\right)}{1-\cos\left(\frac{D}{\lambda}\right)}}\cdot\frac{1}{\sin\left(\frac{x}{\lambda}\right)}.$$

The initial temperature represents the state before the heating source has occurred. The suggested solution may be expanded to the other two coordinates as well. For example, the λ constant is practically the distance from the heat source. To determine the achieved temperature correctly, the following expression is applied (9):

(9) $$U(D/2)=U_0\frac{e^{-\frac{k\cdot t_{\mathrm{f}}}{\lambda^2}}\cdot\sin\left(\frac{D}{\lambda}\right)}{\sin\left(\frac{D/2}{\lambda}\right)\cdot\left(1-\cos\left(\frac{D}{\lambda}\right)\right)}+$$
$$+\frac{P_{\mathrm{device}}}{\alpha\cdot D},\ \lambda=D$$

where U_0 is the initial temperature (in this case 20°C), k is silicon thermal diffusivity, t_{f} is the time, in which the device achieves steady temperature, λ represents the average distance from the heat source (in this case it is exactly equal to the semiconductor device thickness), D is the semiconductor device thickness, P_{device} is the power dissipation of the device, σ represents silicon thermal conductivity. It is important to notice that expression (9) consists of transient contribution and constant contribution. Transient contribution occurs as a reaction to the temperature difference between surroundings and the device. Meanwhile, power dissipation of the diode, which is caused by Joule heating, is a constant source of heating ($P_{\mathrm{device}}/\alpha\cdot D$). If a source of heat is only a part of the region with higher temperature, generated independently from the device, the expression (9) does not include the self-dissipation. Expression (9) is carried out for the general case and it has already been applied on another thermal problem of transformer heating.

Experimental measurements of the power dissipation and temperature

Experimental setup scheme is shown in Fig. 3. The complete experimental system contains a DC-DC boost converter (increases DC voltage) with one branch and DC-AC converter with two branches of power modules (three branches). Power dissipation distributes among all three branches evenly and along individual branch it distributes in regards to the power devices volume. The power dissipation divides according to the following rule, (10):

(10) $$P_{\mathrm{dissipation}}=P_{\mathrm{diode}}+P_{\mathrm{tr}}$$
$$=0.54\cdot P_{\mathrm{dissipation}}+0.46\cdot P_{\mathrm{dissipation}}$$

where $P_{\mathrm{dissipation}}$ represents the total power dissipation of one branch, P_{diode} is the power dissipation of the diode and P_{tr} is the power dissipation of the IGBT transistor.

The measured input current $i_1=I_{\mathrm{DC}}$ is DC quantity (as it is shown in Fig. 3.), as well as the measured input voltage $u_1=U_{\mathrm{DC}}$. Due to the DC-AC converter, which is mounted on the output, the output quantities (i_2 and u_2) are considered with their RMS values. Power dissipation is determined as a difference between input and output power and divided on three branches evenly. Along each branch, power dissipation distributes among components due to the rule described above. Obtained power dissipation is used further in FE calculations, as heat source. Temperature is measured with spot infrared thermometer, which determines the temperature at a particular spot on the surface of the heat sink. Just below that particular spot, a semiconductor device respectively silicon crystal is located

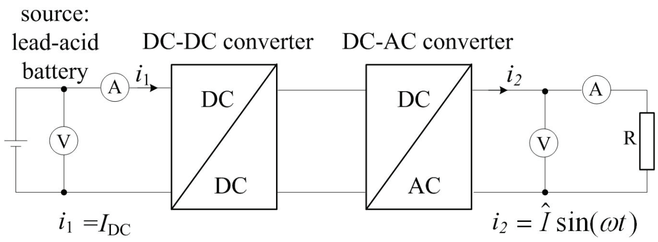

Fig. 3. Experimental setup

Finite element model and numerical thermal analysis

The FEM solver solves the partial differential equation with respect to the given coordinates and uses the temperature scalar potential to calculate the temperature distribution [4]. Heat sources are obtained from the physical system and from the performed measurements. The FE model is geometrically built as the original 3D power model geometry and it contains every detail. The aluminium bonding wires (interconnections) are modelled separately. The FE model is shown in Fig. 4.

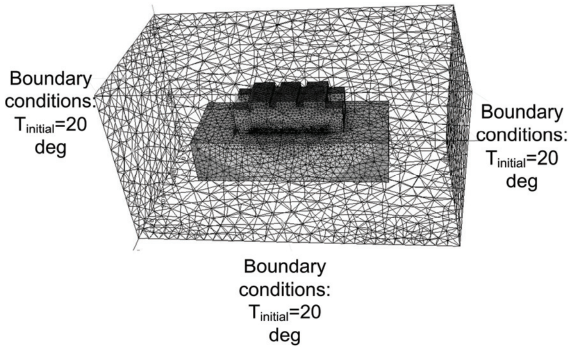

Fig. 4. FE model of the half-bridge power module, including the heat sink

The numerical 3D model contains more than 1,000,000 finite elements. The power module is placed in the room with the temperature of $20^{\circ}\mathrm{C}$. Therefore, the boundary conditions represent are $T_{\mathrm{initial}} = 20^{\circ}\mathrm{C}$. The temperature distribution is calculated on the basis of the previously determined or measured IGBT module power dissipation. In this case, there are two methods to obtain power dissipation. It can be measured or calculated by FEM transient analysis. The second suggestion requires detailed information on electrical current through diodes and transistors. Electrical current through the devices represent current sources and sinks. FE solver calculates power dissipation in each device with certain numerical error. The obtained numerical errors are accumulated and transferred further on to the following FE calculation of the temperature distribution. Due to the better accuracy, the power dissipation is obtained from verified measurements.

Comparison of the analytical, numerical and experimental results

The semiconductor devices have been loaded differently, from minimum to maximum. Table 1 represents different cases of power dissipation of semiconductor devices. Individual temperatures refer to the following: T_1 is temperature measured on the heat sink with infrared spot thermometer; T_2 is temperature on the heat sink calculated with FEM, T_3 is temperature on the heat sink calculated analytically, T_4 is temperature of the diode calculated with FEM and T_5 is temperature of the diode calculated analytically.

Table 1. Power dissipation for different cases and for different loading of devices

Case	a	b	c	d	Worst case	Worst case
P_{diode} (W)	17.8	24.8	28.1	36.7	54	54
P_{tr} (W)	15.2	21.2	23.9	31.3	46	46
Forced cooling	NO	NO	YES	NO	YES	NO
T_1 (°C)	56	/	48	64	/	/
T_2 (°C)	59	75	50	86	80	112
T_3 (°C)	62	78	/	82	/	119
T_4 (°C)	65	87	55	102	93	138
T_5 (°C)	68	83	/	108	/	145

Worst case represents the maximum possible loading of semiconductor devices (maximum power dissipation). In this case, only the temperature of the diode has been observed, because the diode heats more in comparison to the IGBT transistor, which is physically larger. The maximum temperature is the main objective of discussion. Another important observation criterion, which is also measurable, is the temperature of the heat sink that is located just below the diode. Since the temperature of the devices cannot be measured (experimental measurements are shown for the heat sink only as it is shown in Table I), numerical and analytical approach is a good choice to calculate the temperature of the semiconductor device itself. Two cases of six have included a forced cooling (random or oriented in *x*-direction). FE model has included these circumstances as well. However, the additional air motion has not been included in analytical solution, since it had been difficult to describe the phenomena of randomly circulating air. The temperature behaviour due to the different cases of power dissipation of the diode is shown in Fig. 5.

The agreement between analytical and numerical results is good. The absolute temperature error is not higher than ΔT=7°C. The relative error when considering the maximum deviations does not exceed 5%. Heat sink temperature has even a better agreement among results. In the cases of lower loading of the diode (less power dissipation), temperature difference between the diode and the heat sink is lower. Once the temperature of the diode rises, the temperature difference between surrounding air and the device is higher, and, consequently spontaneous self-cooling becomes more efficient.

Therefore, the heat sink temperature does not change so fast when the power dissipation of the devices increases. Different power dissipation cases give the similar temperature distribution; although the temperature values are different (scale is different). The exception is two cases, which include the forced cooling. The temperature distribution for the power dissipation case “d” is shown in Fig. 6. Simulations allow to include forced cooling, so the maximum temperature decreases notably, as it is shown in Fig. 7.

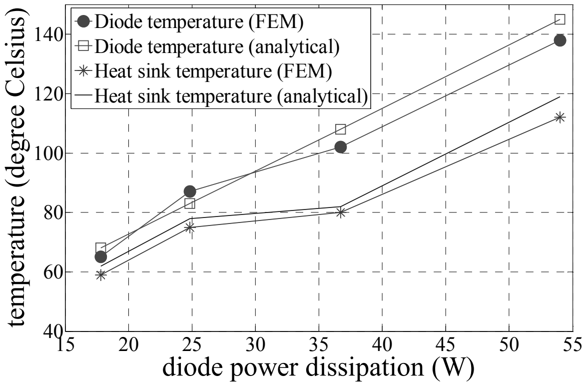

Fig. 5. Calculated temperature of the diode and heat sink for different power dissipation

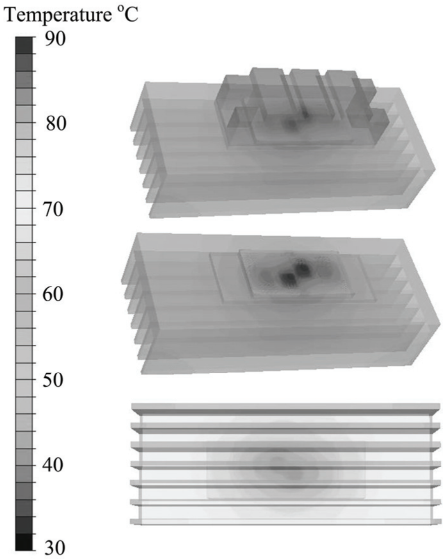

Fig. 6. Temperature distribution for the loading case 'd'

Conclusion

The research describes analytical, numerical and experimental analysis of the temperature for the power module. The power dissipation has been determined experimentally and applied to the analytical analysis and numerical FE model. The maximum temperature on the particular spot of the aluminium heat sink, which had been calculated with FEM and heat equation, has achieved good agreement with experimentally measured temperature.

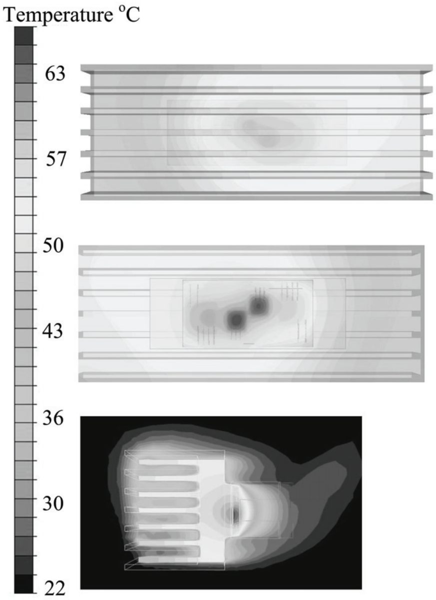

Fig. 7. Temperature distribution for the loading case 'd' with forced cooling included

Therefore, the maximum temperature of 'the worst case' with and without forced cooling has been predicted, although it has not been measured yet. The numerical model has shown good accuracy and it has included all important physical properties of the region, as well as the forced cooling. Analytical solution has not included forced cooling because of the additional difficulty of the already complex system. However, the analytical solution is applicable on systems with the similar physical properties as it is, for example, a thermal analysis of a transformer.

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