WARWICK
THE UNIVERSITY OF WARWICK

Manuscript version: Author's Accepted Manuscript
The version presented in WRAP is the author's accepted manuscript and may differ from the published version or Version of Record.

Persistent WRAP URL:
http://wrap.warwick.ac.uk/167354

How to cite:
Please refer to published version for the most recent bibliographic citation information. If a published version is known of, the repository item page linked to above, will contain details on accessing it.

Copyright and reuse:
The Warwick Research Archive Portal (WRAP) makes this work by researchers of the University of Warwick available open access under the following conditions.

Copyright © and all moral rights to the version of the paper presented here belong to the individual author(s) and/or other copyright owners. To the extent reasonable and practicable the material made available in WRAP has been checked for eligibility before being made available.

Copies of full items can be used for personal research or study, educational, or not-for-profit purposes without prior permission or charge. Provided that the authors, title and full bibliographic details are credited, a hyperlink and/or URL is given for the original metadata page and the content is not changed in any way.

Publisher's statement:
Please refer to the repository item page, publisher's statement section, for further information.

For more information, please contact the WRAP Team at: wrap@warwick.ac.uk.

warwick.ac.uk/lib-publications

Junction Temperature Estimation Method in Multichip IGBT Module Based on TSEPs

Jianxiong Yang[1] · Yanbo Che[1*] · Li Ran[2,3] · Mingxing Du[4]

Abstract

With the development of high-power converter, safe operation of IGBT modules with parallel chips is of increasing importance. In multichip module, the uneven solder layer degradation of parallel chips leads to junction temperature difference between chips. However, the specific situation of the junction temperature represented by the external electrical characteristics of the module is not clear when the junction temperature difference occurs in the internal chip of multichip IGBT module. This paper studies the physical meaning of junction temperature estimated based on threshold voltage, maximum collector emitter voltage change rate and maximum collector current change rate by experiment. The experimental results show that the temperature estimated from the threshold voltage is very close to the highest temperature of all the chips inside the module, and the junction temperature estimated from the maximum collector emitter voltage change rate and maximum collector current change rate is very close to the average temperature.

Keywords multichip IGBT module, junction temperature, threshold voltage, collector emitter voltage change rate, collector current change rate

1 Introduction

As the foundation and core component of power electronic system, power module is the "hub" of power conversion and control [1], which is in a very severe working condition [2], and will withstand more than five million power cycles in its life cycle [3], so the aging problem is inevitable. According to the industrial survey, about 34% of converter failures are caused by device failures [4], and 55% of system failures are mainly caused by temperature [5]. In addition, studies have shown that the failure rate of power devices will double when the temperature increased by 10 ℃ [6]. Therefore, it is very important to monitor the junction temperature of IGBT module accurately: 1) the change of junction temperature will affect the physical parameters of semiconductor and change its characteristics; 2) Any change of IGBT health state caused by common faults of power module (such as bond wire lift off and solder layer fatigue) is reflected in the change of IGBT junction temperature. Auxiliary manual intervention can prolong the service lifetime of the device. 3) Improving the power density of IGBT power module, improving the system reliability and reducing the cost.

At present, there are four popular junction temperature monitoring estimation methods in the world: physical contact methods, optical methods, thermal impedance model prediction and thermo-sensitive electric parameters (TSEPs). The physical contact measurement method is to put the thermal sensor directly on the IGBT chip to measure the junction temperature [7-8]. Although this method is simple with low cost, it has strong invasiveness and slow response speed. The optical measurement method mainly uses the infrared camera to image the object temperature [9-10]. This method has high accuracy and can measure the surface temperature field distribution of the die, but the cost is high. It is necessary to open the package of the tested module for accurate measurement. The thermal impedance model prediction method is to simulate the junction temperature distribution through finite element method when the power loss and thermal impedance model are determined [11-12]. Although this method is non-invasive, it is affected by the time-varying thermal resistance network parameters, resulting in the error of junction temperature prediction [13]. The physical properties of semiconductor materials are closely related to temperature. For example, the carrier concentration and lifetime in silicon materials are positively proportional to temperature, whereas the mobility is inversely proportional to temperature [14]. The external characteristics of semiconductor devices show a monotonous trend with temperature, and the method of

---

[*] Yanbo Che
Email:lab538@163.com

[1] School of Electrical and Information Engineering, Tianjin University, Tianjin, China.

[2] School of Electrical Engineering, Chongqing University, Chongqing, China

[3] School of Engineering, University of Warwick, Coventry, U.K.

[4] School of Electrical and Electronic Engineering, Tianjin University of Technology, Tianjin, China.

using this relationship to obtain the junction temperature is called the thermo-sensitive electric parameters. The chip itself is equivalent to a temperature sensor offering the advantages of non-invasive measurement, low hardware cost, fast response speed, and no effect on the reliability of the device. It has become a research hotspot of IGBT junction temperature extraction. Moreover, it is considered as the most potential on-line junction temperature extraction method for industrial applications.

Most studies regarding the monitoring of chip junction temperature by TSEPs mainly focuses on single-chip power modules. Commonly used TSEPs include Miller plateau duration [15], voltage change rate between collector and emitter [16], short circuit current [17], turn-on/turn-off delay time [18], threshold voltage [19], gate current [20], collector-emitter voltage [21], etc. However, with the development of high-power converters, safe operation of IGBT modules with parallel chips is of increasing importance [22]. In the case of multichip modules, given that the electrothermal characteristics of the chips cannot be absolutely identical, together with the non-uniformity of the cooling system and working conditions of each chip, some chips will be subject to higher stresses. The solder layers of the most stressed chip will degrade first. Meanwhile, the increased thermal resistance would accelerate the aging process, and cause the uneven degradation in a multi-device system [23]. It can be shown that the response of some TSEPs, may reduce to such a level that they are no longer meaningful in a multichip system with degradation of the solder layer under a single chip. In the case of one IGBT die, the estimated temperature can be regarded as the junction temperature of die in concern. But what could happen if two or more dies are paralleled and the temperature is estimated? From the point of view of application, the condition monitoring technology of power module with parallel chip is urgently needed.

In this paper, the physical significance of junction temperature estimated based on threshold voltage, maximum collector emitter voltage change rate and maximum collector current change rate is clarified. The experiments show that the temperature estimated from the threshold voltage is very close to the highest temperature of all the chips inside the module, and the junction temperature estimated from the collector current change rate and collector emitter voltage change rate is very close to the average temperature.

The remainder of this paper is organized as follows: Section 2 clarifies the physical significance of junction temperature estimated based on the TSEPs in a multichip module. The experimental verification is presented in 3. Finally, Section 4 concludes the paper.

2 Analysis of Temperature Estimation for TSEPs in Multichip Module

The current carrying capacity of the IGBT module is enhanced by connecting multiple chips in parallel. They are considered as a promising solution to increase the module or converter capacity. In this section, the physical significance of the temperature estimated from the three dynamic TSEPs in a multichip power module will be described in detail.

2.1 Threshold Voltage

Since the multiple chips operate in parallel, as long as the gate voltage reaches the threshold voltage of one of the chips, the whole module will allow current to flow and hence start to turn on. From equation (1), the threshold voltage decreases with the temperature. Therefore, the higher the chip temperature is, the lower will be the threshold voltage and the sooner will the gate voltage reach the lowest threshold voltage resulting in the entire module to turn on. The chip with the highest temperature will turn on first and be subject to huge current stress at the moment of module switching on, causing further temperature rise through a positive feedback mechanism. Therefore, this is identified as the chip with the worst stress and being most prone to aging and eventual failure. The expression of threshold voltage of a multichip power module is

$$V_{thp}(T)=V_{th}(T_{max}) \qquad (1)$$

Consequently, the temperature estimated from the threshold voltage is the highest temperature of all the chip inside the multichip power module.

2.2 Maximum Collector Emitter Voltage change rate during turn-off

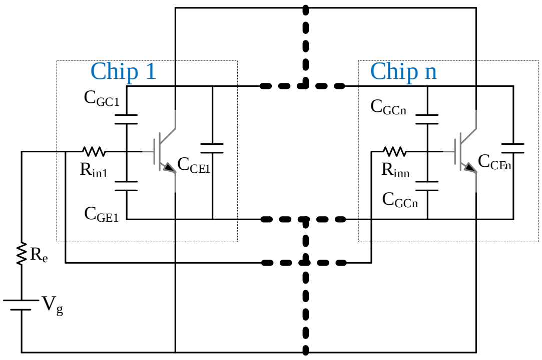


Fig. 1 Equivalent circuit model of n IGBT chips in parallel.

The equivalent circuit model of n IGBT chips in parallel is shown in Fig.1, and the gate current i_g is obtained as follows

$$i_{\mathrm{g}}(t)=\sum_{z=1}^{n} i_{\mathrm{gz}}(t) \tag{2}$$

During the turn-off period, the collector emitter voltage increases rapidly when the gate current charges the Miller capacitor, and the collector emitter voltage change rate reaches the maximum value, which is [16]

$$\frac{\mathrm{d}v_{ce}}{\mathrm{d}t}_{\max}=\frac{i_g}{C_{\mathrm{gc}}(T)}=\frac{\sum_{z=1}^{n} i_{\mathrm{gz}}(t)}{\sum_{z=1}^{n} C_{\mathrm{gcz}}(T)} \tag{3}$$

$$C_{\mathrm{gc}}(T)=\frac{C_{ox}A\sqrt{\dfrac{q\cdot N_{\mathrm{B}}(T)\cdot\varepsilon}{2V_{ce}}}}{C_{ox}+A\sqrt{\dfrac{q\cdot N_{\mathrm{B}}(T)\cdot\varepsilon}{2V_{ce}}}}\propto N_{\mathrm{B}}(T)\propto kT \tag{4}$$

where, C_{gcz} is the gate-collector capacitances of Chip z. From equations (3) and (4), the relationship between maximum collector emitter voltage change rate and temperature is obtained when n chips are in parallel can be obtained

$$\frac{\mathrm{d}v_{ce}}{\mathrm{d}t}_{\max}=\frac{\sum_{z=1}^{n} i_{\mathrm{gz}}(t)}{k\sum_{z=1}^{n} T_z} \tag{5}$$

When all the internal chips show the external module temperature

$$\frac{\mathrm{d}v_{ce}}{\mathrm{d}t}_{\max}=\frac{\sum_{z=1}^{n} i_{\mathrm{gz}}(t)}{nkT_j} \tag{6}$$

where T_{j} is the estimated temperature from TSEPs in multichip power module. From equations (5) and (6), we have

$$T_j=\frac{1}{n}\sum_{z=1}^{n} T_z \tag{7}$$

Then the temperature estimated from the maximum collector emitter voltage change rate should be the average temperature of all the chip inside the multichip power module.

2.3 Maximum collector current change rate during turn-off

For inductive load, the maximum change rate of collector current is [24]

$$\frac{\mathrm{d}i_c}{\mathrm{d}t}_{\max}=\frac{-2I_{\mathrm{L}}}{\tau\left(\dfrac{T+273.15}{300}\right)^{1.5}}\approx\frac{-I_{\mathrm{L}}}{\tau(0.003T+0.42)} \tag{8}$$

where, τ is the large injection lifetime in the cut-off layer at 26.85 ℃, and I_{L} is the load current. Therefore, the relationship between the maximum collector current change rate and temperature is obtained when n chips are in parallel can be obtained

$$\frac{\mathrm{d}i_{\mathrm{c}}}{\mathrm{d}t}_{\max}=\frac{-\mathrm{d}\sum_{z=1}^{n} i_{\mathrm{cz}}}{\mathrm{d}t}_{\max}=\frac{-I_{\mathrm{L}}}{\tau\sum_{z=1}^{n} 0.003T_z+0.42n\tau} \tag{9}$$

When all the internal chips show the external module temperature

$$\frac{\mathrm{d}i_{\mathrm{c}}}{\mathrm{d}t}_{\max}=\frac{-I_{\mathrm{L}}}{0.003\tau nT_{\mathrm{j}}+0.42n\tau} \tag{10}$$

where T_{j} is the estimated temperature from TSEPs in multichip power module. From equations (9) and (10), we have

$$T_j=\frac{1}{n}\sum_{z=1}^{n} T_z \tag{11}$$

Then the temperature estimated from the maximum collector current change rate should be the average temperature of all the chip inside the multichip power module.

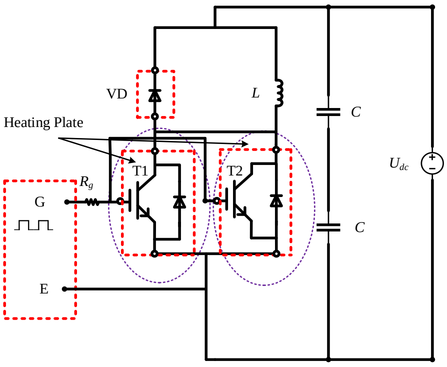
3 Experimental Verification

3.1 Experimental Platform

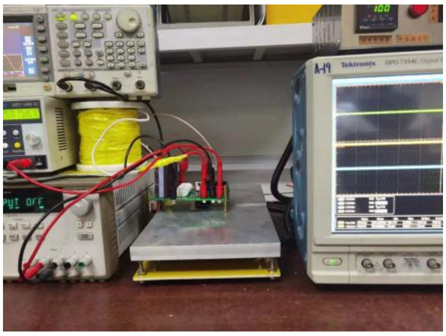
In order to verify the theoretical derivation and the physical significance of temperature estimation in a multichip module, two parallel IGBTs are tested with double pulse under the same driving signal. The Infineon trench-gate IGBTs IHW25N120R2(1200V,25A) are chosen as the DUTs (device under tests). The test circuit and test bench are shown in Fig. 2, where U_{dc} is DC link voltage, C the DC bus capacitance, the upper leg is silicon PiN diode in anti-parallel with load inductance L, and the lower leg is tested device the paralleled IGBTs T1 and T2. This topology is used to test a single device or two devices in parallel. The first pulse is used to control for the load current approach the set value and the second pulse is to measure u_{ce} and i_c during the IGBT turn-on and off. To simulate the switching characteristics of parallel IGBTs at different junction temperatures, two electric heating plates with temperature control are placed under T1 and T2 respectively to warm them precisely.

Before the test, the basement of T1 and T2 are warmed for 20 minutes to ensure thermal equilibrium [25], which means that the junction temperature and case temperature are about equal to the temperature measured at the heating plate. Then the paralleled IGBTs are triggered with the gating pulse and the measurement starts. A series of characteristics of IGBT under different temperature difference can be obtained by adjusting the temperature of electric heating plate.

The same model and batch of products are selected to parallel to eliminate the influence of inconsistency of the IGBT's own parameters on the test results. The circuit layout is symmetrical and the lead wire is as short as possible to eliminate the influence of the layout of the external circuit on the test results. By adjusting the temperature of each electric heating plate, different temperature difference is created. Changing the width of the first pulse to construct different total load current I_{all}. The experiment process is repeated to get the switching process with different temperature difference and different total current level.



(a) Test circuit



(b) Test bench

Fig. 2 Double test circuit and test bench.

3.2 Threshold Voltage

The turn-on waveforms of V_{ge} and I_c, for two parallel IGBTs at the same temperature and 500V&45A, are obtained by heating up the two parallel IGBTs to the same temperature, and the results are shown in Fig. 3. The measurement of the threshold voltage is based on the value of the gate-emitter voltage obtained at the moment of the IGBT being turned-on. The datasheet of the IGBT used in the experiment suggests the corresponding gate-emitter voltage when the value of conduction current is 0.58mA. It can be seen that threshold voltage decreases with temperature, exhibiting negative temperature dependence. Fig. 4 shows the relationship between threshold voltage V_{th} and temperature when the conduction current is 10mA, 30mA and 60mA respectively. It can be seen that V_{th} varies linearly with the measured temperature, so this parameter can be used to estimate the IGBT junction temperature. The temperature sensitivity under different conduction current almost the same, which equals to 9.64mV/°C approximately. The look up table of threshold voltage could be constructed.

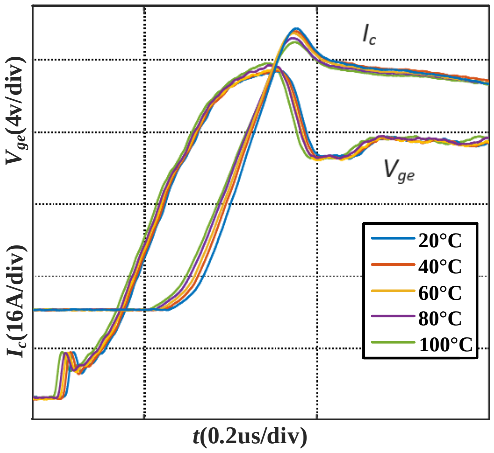


Fig. 3 Turn on waveforms of V_{ge} and I_c for a series of parallel IGBTs at the same temperature at 500V&45A.

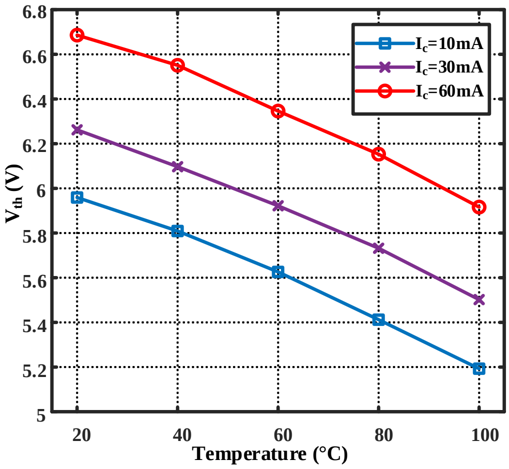


Fig. 4 Relationship between threshold voltage and temperature when conduction current is 10mA, 30mA and 60mA respectively.

The turn on waveforms of V_{ge} and I_c for a series of parallel IGBTs at different temperatures at 500V&45A are obtained by heating the two parallel IGBTs to different temperatures, as shown in Fig. 5. According to above, the temperature sensitivity under different value of conduction current is almost the same, hence, the corresponding gate-emitter voltage of 60 mA conduction current is chosen to obtain the threshold voltage. The temperature estimated by the threshold voltage look-up table is shown in Table 1. For example, when the high temperature IGBT chip is heated to 40°C and the low temperature IGBT chip is heated to 25°C, the temperature estimated through the threshold voltage is 37.51°C, which is close to the highest temperature of the parallel chip. The estimated temperature was always within 3 °C of the highest temperature of the parallel chip all the tested conditions. Therefore, it is verified that the temperature estimated from the threshold voltage was found to be very close to the highest temperature of all the chips inside the module.

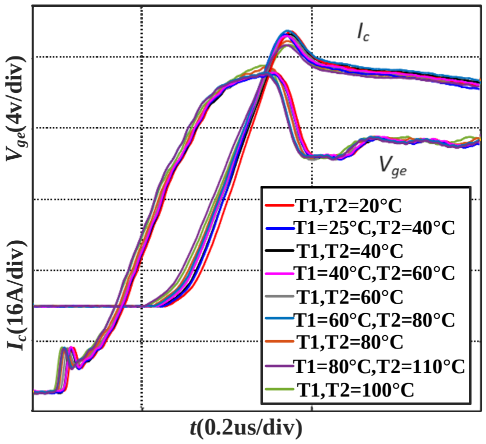


Fig. 5 Turn on waveforms of V_{ge} and I_c for a series of parallel IGBTs at different temperatures at 500V&45A.

Table 1 T_j (°C) estimated by V_{th} when IGBT heated to different temperatures

High(℃)	Low(℃)	Average(℃)	Estimate (℃)
40	25	32.5	37.51
60	40	50	58.78
80	60	70	78.04
110	80	95	107.12

3.3 Maximum Collector Emitter Voltage change rate during turn-off

The waveforms of dV_{ce}/dt during turn-off, for two parallel IGBTs at the same temperature and 500V&45A, are obtained by heating up the two parallel IGBTs to the same temperature, and the results are shown in Fig. 6. It can be seen that maximum collector emitter voltage change rate decreases with increasing temperature, exhibiting negative temperature dependence. Fig. 7 shows the relationship between maximum collector emitter voltage change rate and temperature. It is obvious that dV_{ce}/dt_{max} varies linearly with the measured temperature, so this parameter can also be used to estimate the IGBT junction temperature. It is found that the temperature sensitivity is about 9.43V/us*°C under 500V&45A switching conditions, and it is possible to create look-up table of maximum collector emitter voltage change rate.

The waveforms of dV_{ce}/dt during turn-off, for two parallel IGBTs at the different temperature and 500V&45A, are obtained by heating up the two parallel IGBTs to different temperature, as shown in Fig. 7. The temperature estimated from the maximum collector emitter voltage change rate look-up table is shown in Table 2. For example, when the high temperature IGBT chip is heated to 60°C and the low temperature IGBT chip is heated to 40°C, the temperature estimated through the threshold voltage is 47.40°C, which is close to the average temperature of the parallel chip. The estimated temperature was always within 3 °C of the average temperature of the parallel chip all the tested conditions. Therefore, it is verified that the temperature estimated from the maximum collector emitter voltage change rate was found to be very close to the average temperature of all the chips inside the module.

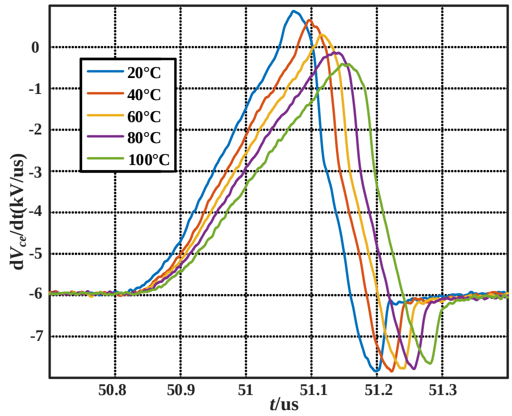


Fig. 6 The waveforms of dV_{ce}/dt for a series of parallel IGBTs at the same temperature at 500V&45A.

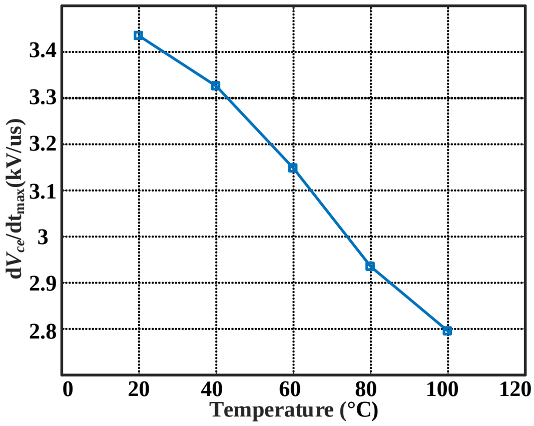


Fig. 7 Relationship between dV_{ce}/dt_{max} and temperature at 500V&45A switching conditions.

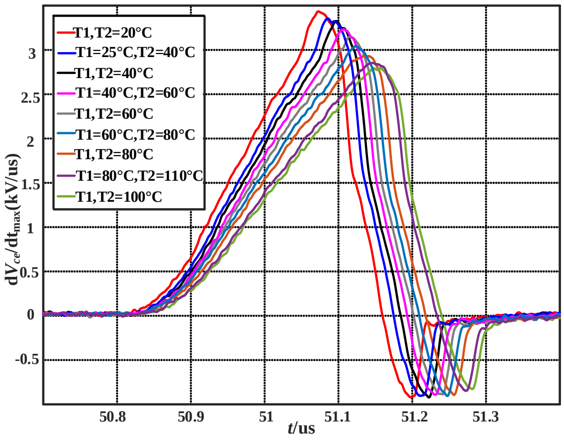


Fig. 8 The waveforms of dV_{ce}/dt for a series of parallel IGBTs at the different temperature at 500V&45A.

Table 2 T_j (ºC) estimated by dV_{ce}/dt when IGBT heated to different temperatures

High(℃)	Low(℃)	Average(℃)	Estimate (℃)
40	25	32.5	32.79
60	40	50	47.40
80	60	70	70.14
110	80	95	92.98

3.4 Maximum Collector Current change rate during turn-off

The waveforms of di_c/dt during turn-off, for two parallel IGBTs at the same temperature and 500V&45A, are obtained by heating up the two parallel IGBTs to the same temperature, and the results are shown in Fig. 9. It can be seen that maximum collector current change rate decreases with increasing temperature, exhibiting negative temperature dependence. Fig. 10 shows the relationship between maximum collector current change rate and temperature. It is obvious that di_c/dt_{max} varies linearly with the measured temperature, so this parameter can also be used to estimate the IGBT junction temperature. It is found that the temperature sensitivity is about 13.55A/us*ºC under 500V&45A switching conditions, and it is possible to create look-up table of maximum collector current change rate.

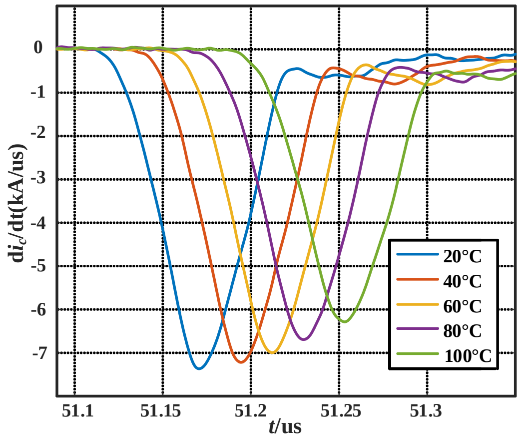


Fig. 9 The waveforms of di_c/dt for a series of parallel IGBTs at the same temperature at 500V&45A.

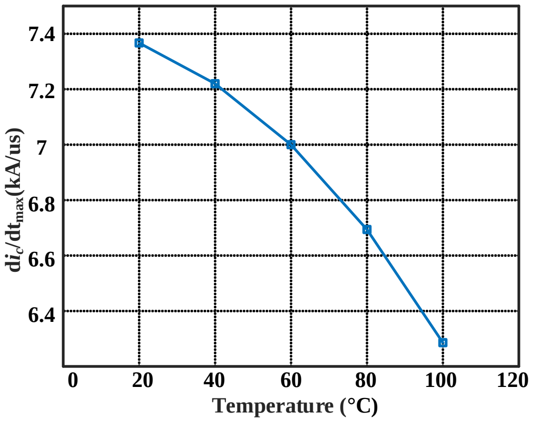


Fig. 10 Relationship between di_c/dt_{max} and temperature at 500V &45A switching conditions.

The waveforms of di_c/dt during turn-off, for two parallel IGBTs at the different temperature and 500V&45A, are obtained by heating up the two parallel IGBTs to different temperature, as shown in Fig. 11. The temperature estimated from the maximum collector current change rate look-up table is shown in Table 3. For example, when the high temperature IGBT chip is heated to 60°C and the low temperature IGBT chip is heated to 40°C, the temperature estimated through the threshold voltage is 46.06°C, which is close to the average temperature of the parallel chip. The estimated temperature was always within 4 ºC of the average temperature of the parallel chip all the tested conditions. Therefore, it is verified that the temperature estimated from the maximum collector current change rate was found to be very close to the average temperature of all the chips inside the module.

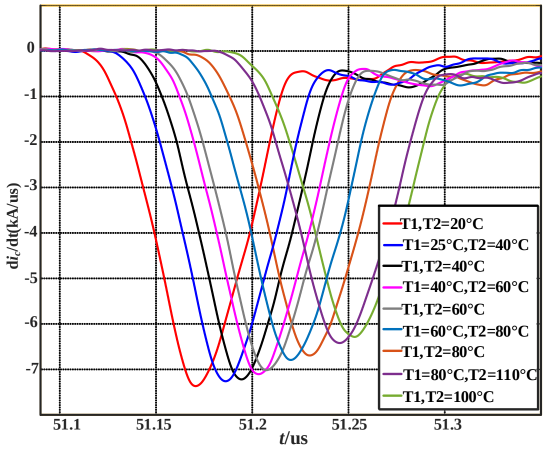


Fig. 11 The waveforms of di_c/dt for a series of parallel IGBTs at the different temperature at 500V&45A.

Table 3 T_j (ºC) estimated by di_c/dt when IGBT heated to different temperatures

High(℃)	Low(℃)	Average(℃)	Estimate (℃)
40	25	32.5	34.22
60	40	50	46.06
80	60	70	69.05
110	80	95	96.73

4 Conclusion

In this paper, the relationship between the terminal characteristics of a multichip IGBT module and the junction temperature of internal chips is analyzed. The physical significance of the chip temperature estimated based on threshold voltage, maximum collector emitter voltage change rate and maximum collector current change rate is clarified. Parallel discrete devices are used to simulate multichip IGBT power module for experimental verification. The experimental results show that:

1) the temperature estimated from the threshold voltage

is going to be very close to the highest temperature of all the chips inside the module, and that estimated from the maximum collector emitter voltage change rate or maximum collector current change rate is going to be very close to the average temperature.

2) the estimated temperature by threshold voltage was always within 3 ºC of the highest temperature of the parallel chip under all the tested conditions, and the estimated temperature from maximum collector emitter voltage change rate or maximum collector current change rate was always within 3°C or 4°C of the average temperature of the parallel chips respectively.

3）the foundation device model is not itself novel. But it is used to show a phenomenon in an IGBT module with parallel chips, which leads to a new technique to model the health condition of the module.

5 Acknowledgments

This work was supported by National Key Research and Development Program of China (2018YFB0905803) and Tianjin postgraduate research and innovation project 2020 (2020YJSB007).

References

1. He X.N., Wang R.C., Wu J.D., et al.: Info character of power electronic conversion and control with power discretization to digitization then intelligentization. Proceedings of the CSEE, 40(5), 1579-1587 (2020).
2. Chen X.X., Liu J.J., Deng Z.F., et al.: A diagnosis strategy for multiple IGBT open-circuit faults of modular multilevel converters. IEEE Trans. on Power Elec., 36(1), 191-203 (2021).
3. Dupont L., Avenas Y., Jeannin P.: Comparison of junction temperature evaluations in a power IGBT module using an IR camera and three thermosensitive electrical parameters. IEEE Trans. Ind. Appl., 49(4), 1599-1608 (2013).
4. Yang S.Y., Xiang D.W., Bryant A., et al.: Condition monitoring for device reliability in power electronic converters: a review. IEEE Trans. on Power Elec., 25(11), 2734-2752 (2011).
5. Yang S.Y., Bryant A., Mawby P., et al.: An industry-based survey of reliability in power electronic converters. IEEE Trans. Indus. Appli., 47(3), 1441-1451 (2011).
6. Fabis P.M., Shum D., Windischmann H.: Thermal modeling of diamond-based power electronics packaging. Fifteenth Annual IEEE Semiconductor Thermal Measurement and Management Symposium (1999).
7. Li J.M., Zhou Y.G., Qi Y.D., et al.: In-situ measurement of junction temperature and light intensity of light emitting diodes with an internal sensor unit. IEEE Electron Device Letters, 36(10), 1082-1084 (2015).
8. Soldati A., Delmonte N., Cova P., et al.: Device-sensor assembly FEA modeling to support kalman-filter-based junction temperature monitoring. IEEE Journal of Emerging and Selected Topics in Power Electronics, 7(3), 1736-1747 (2019).
9. Baker N., Dupont L., Nielsen S.M., et al.: IR camera validation of IGBT junction temperature measurement via peak gate current. IEEE Trans. on Power Elec., 32(4), 3099-3111 (2017).
10. Eleffendi M.A. and Johnson M.: Application of kalman filter to estimate junction temperature in IGBT power modules. IEEE Trans. on Power Elec., 31(2), 1576-1587 (2016).
11. Hu Z., Du, M.X., Wei K.X., et al.: An adaptive thermal equivalent circuit model for estimating the junction temperature of IGBTs. IEEE Journal of Emerging and Selected Topics in Power Electronics, 7(1), 392-403 (2019).
12. Avenas Y., Dupont L. and Khatir Z.: Temperature measurement of power semiconductor devices by thermo-sensitive electrical parameters: A review. IEEE Trans. on Power Elec., 27(6), 3081-3092 (2012).
13. Chen M., Hu A., Tang Y., et al.: Modeling analysis of IGBT thermal model. High Voltage Engineering, 37(2), 453-459 (2011).
14. Sun P., Zhao Z., Cai Y., et al.: Analytical model for predicting the junction temperature of chips considering the internal electrothermal coupling inside SiC metal-oxide-semiconductor field-effect transistor modules. IET Power Electron., 13(3), 436-444 (2020).
15. Liu J.C., Zhang G.G., Chen Q., et al.: In situ condition monitoring of IGBTs based on the miller plateau duration. IEEE Trans. Power Electron., 34(1), 769-782 (2019).
16. Bryant A., Yang S.Y., Mawby P.: Investigation into IGBT dV/dt during turn-off and its temperature dependence. IEEE Trans. Power Electron., 26(10), 3019-3031 (2011).
17. Xu Z.X., Xu F. and Wang F.: Junction temperature measurement of IGBTs using short-circuit current as a temperature-sensitive electrical parameter for converter prototype evaluation. IEEE Trans. Ind. Electron., 62(6), 3419-3429 (2015).
18. Luo H.Z., Chen Y.X., Sun P.F., et al.: Junction temperature extraction approach with turn-off delay

time for high-voltage high-power IGBT modules. IEEE Trans. Power Electron., 31(7), 5122-5132 (2016).

19. Zeng G., Cao H., Chen W., et al.: Difference in device temperature determination using p-n-junction forward voltage and gate threshold voltage. IEEE Trans. Power Electron., 34(3), 2781-2793 (2019).
20. Baker N. and Iannuzzo F.: The temperature dependence of the flatband voltage in high power IGBTs. IEEE Trans. Ind. Electron., 66(7), 5581-5584 (2019).
21. Baker N., Munk-Nielsen S., Iannuzzo F., et al.: IGBT junction temperature measurement via peak gate current. IEEE Trans. Power Electron., 31(5), 3784-3793 (2016).
22. Peralta J., Saad H., Dennetiere S., et al.: Detailed and averaged models for a 401-Level MMC-HVDC system. IEEE Trans. Power Del., 27(3), 1501-1508 (2012).
23. Hu B.R., Hu Z.D., Ran L., et al.: Heat-flux-based condition monitoring of multichip power modules using a two-stage neural network. IEEE Trans. Power Electron., 36(7), 7489-7500 (2021).
24. Guo Y.X., Wang X.M. and Zhang B.: Improved IGBT module junction-temperature extraction algorithm and experiment. Journal of Power Supply, 19(1), 205-214 (2021).
25. Chen C.L., Al-Greer M., Jia C.J., et al.: Localization and detection of bond wire faults in multichip IGBT power modules. IEEE Trans. on Power Elec., 35(8), 7804-7815 (2020).