



Article A Fault Detection Method of IGBT Bond Wire Fatigue Based on the Reduction of Measured Heatsink Thermal Resistance

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Abstract: Bond wire lift-off is one of the major failure mechanisms in the insulated gate bipolar transistor (IGBT) modules. Detecting the fault of bond wires is important to avoid the open-circuit fault of IGBT to ensure the reliable operation of power converters. In this paper, we propose a novel bond wire fatigue detection method for IGBT, which could be used in normal working conditions. Firstly, we investigated the dependence of bond wire fatigue on heatsink thermal resistance. An aging rate K was proposed to compare the measured thermal resistance with the initial value, which could indicate the bond wire fatigue. Then, this proposed method was verified by simulation and experimental results under different current levels. Finally, a power cycling test was used to show the aging process of the IGBT module, which shows the feasibility of proposed method.

Keywords: IGBT; bond wire fatigue; Heatsink thermal resistance; fault detection; heat flow

1. Introduction

Power converters are widely used with the rapid development of renewable energy [1]. As the key component of power converters, insulated gate bipolar transistors (IGBTs) are the most adopted power devices [2] according to the demand for operational reliability, energy efficiency, and cost competitiveness.

Figure 1 shows the structure of wire-bonded IGBT, which consists of several layers of different materials. IGBT die is soldered on the direct-bonded copper (DBC) plate, and the DBC plate is soldered on the baseplate. The silicon IGBT die is connected to the substrate by several paralleled aluminum bond wires. As a result of physical limits, a coefficient of thermal expansion (CTE) mismatch occurs between silicon die and aluminum bond wires, causing swelling stress and shrinkage stress during power cycling and finally leading to the bond wire lift-off [3]. Bond wire lift-off is one of the domain failure mechanisms of the IGBT module [4], and it usually appears in the last 10% of the remaining life stage of the module. High-junction temperature fluctuations [5] and high-frequency operation [6] will also accelerate the aging of bond wires. The failure of bond wires in IGBT will easily lead to open-circuit faults and cause damage to the whole system [7]. Consequently, the reliability of bond wires is important for the IGBT module.

The fault detection method could obtain the state of the device, which is important to ensure the safe operation of power converters. Many bond wire failure detection methods have been proposed in recent studies. J. Lehmann [8] presented a modified DCB layout in an IGBT module to measure the fatigue of bond wires. This method needs to change the structure of the IGBT module to set the auxiliary circuit inside. H. Shiratsuchi [9] and H. Tomonaga [10] proposed to monitor IGBT current distribution by the magnetic field, which could be used to show the status of bond wires [11]. These sensors need



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Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). to be integrated into the module to measure the magnetic field. Such methods are capable of detecting the bond wire fatigue; however, the invasive modifications or sensors would bring unpredictable reliability issues to the power module itself. To overcome such challenges, non-invasive detection methods are also proposed. The fatigue of bond wires changes the electrical gate charge circuit, which finally affects the switching process. Hence, these parameters have been used by several researchers to indicate the fault of bond wires, such as gate current [12], charging time [13], transconductance [14], and stray inductance [15]. Although those methods are non-invasive and only gate voltage needs to be measured, the sensitivity and accuracy of the measured results could be easily affected by the high sampling frequency and resolution of gate signal [16]. The on-state voltage of IGBT is independent of the junction temperature at the inflection point, which has a zero-temperature characteristic. Hence, U. Choi [17], A. Singh [18], and M. Du [19] used the conduct voltage at the inflected point with special gate voltage to measure bond wire lift-off, while P. Sun [20] measured the short-current at special gate voltage. Although these methods showed adequate sensitivity to detect the bond wire fault irrespective of the junction temperature, they could only be used at abnormal working conditions. In general, the weaknesses of those detection methods lead to an increase in costs and complexity in normal operations. Therefore, a more convenient detection method is still needed to reflect the health status of bond wires in IGBT modules in normal working conditions.



Figure 1. Structure of wire-bonded IGBT module.

To address this challenge, a novel method is proposed in this paper to detect the bond wire fatigue based on the heatsink thermal resistance decrement, which could be used in normal conditions. Two aspects are demonstrated as follows. (1) The effect of IGBT bond wire lift-off on heatsink thermal resistance measurement is presented. The measured results decrease due to the heat flow of bond wires. (2) A fault detection method based on the reduction in measured heatsink thermal resistance is proposed. In this method, the fault of bond wires is indicated after a decrease in measured results of heatsink thermal resistance, which is independent of the working conditions. By these means, the fault of bond wires could be conveniently detected to avoid open-circuit fault in normal conditions.

The rest of this paper is organized as follows. Our detection method is proposed in Section 2. A multi-physics field FEM model is established to analyze the effect of bond wire lift-off in Section 3. The experimental results verify this method in Section 4. A power cycling test is used to show the aging process in Section 5. Section 6 concludes this paper.

2. Failure Mechanism and Detection Method

2.1. Effect of Bond Wire Lift-Off on Heatsink Thermal Resistance Measurement

Power loss of die P_D is far greater than bond wires P_{WB} in a healthy module [17]; hence, IGBT die is the major heat source in the IGBT module P_{loss} , while the power loss of bond wires is nearly negligible (Equation (1)). The heat mainly concentrates under die and transfers through each layer to the baseplate, and dissipates to the ambient temperature by the heatsink, as shown in Figure 2a.

$$P_{\rm loss} = P_{\rm D} + P_{\rm WB} \stackrel{P_{\rm D} \gg P_{\rm WB}}{\approx} P_{\rm D} \tag{1}$$



Figure 2. (a) Heat flow in healthy module. (b) Thermal network of healthy module.

The case temperature $T_{\rm C}$ rises when the power loss $P_{\rm loss}$ flows through the heatsink to ambient $T_{\rm A}$, which is related to the equivalent thermal resistance of heatsink $Z_{\rm E_{-HS}}$, as in Equation (2).

$$T_{\rm C} = P_{\rm loss} \cdot Z_{\rm E_HS} + T_{\rm A} = P_{\rm D} \cdot Z_{\rm E_HS} + T_{\rm A} \tag{2}$$

The thermal network in the healthy module is shown in Figure 2b. The power loss of die transfers through the IGBT module Z_{JC} and heatsink Z_{HS} to the ambient. Hence, the measured thermal resistance of heatsink could be obtained based on (3), which equals the theoretical value of equivalent thermal resistance of heatsink Z_{E-HS} on the case point.

$$Z_{E_{HS}} = \frac{T_{C} - T_{A}}{P_{loss}} = Z_{HS}$$
(3)

However, the total resistance of parallel bond wires increases after bond wire liftoff [21] which leads to a power loss increase in the remaining bond wires P_{WB} [20], as in Equation (4), where R_{WB} is the resistance of a single bond wire, I_C is the conduction current, N_{wire} is the number of total bond wires, and N_{fail} is the number of broken wires.

$$P_{\rm WB} = I_{\rm C}^2 \cdot R_{\rm WB} / (N_{\rm wires} - N_{\rm fail})$$
⁽⁴⁾

Our previous study [22,23] proposes that the heat flow of bond wires is different from the die, which transfers to both the die side and the emitter side at the same time, as in Figure 3a. Hence, the power loss of bond wires could be divided into two parts based on the direction of heat flow, which transfers through the die side P_{WB-D} and emitter side P_{WB-E} , as in Equation (5).

$$P_{\rm WB} = P_{\rm WB_D} + P_{\rm WB_E} \tag{5}$$



Figure 3. (a) Heat flow after bond wire lift-off. (b) Thermal network of IGBT module after wire lift-off.

Only P_{WB_D} transfers through die to the case point and dissipates to ambient temperature by heatsink with die power loss. This power loss P'_{loss} on case point finally causes a temperature rise on the heatsink T'_C , as in Equations (6) and (7).

$$P_{\rm loss}' = P_{\rm D} + P_{\rm WB_{-}D} \tag{6}$$

$$T'_{\rm C} = P'_{\rm loss} \cdot Z_{\rm E_HS} + T_{\rm A} = (P_{\rm D} + P_{\rm WB_D}) \cdot Z_{\rm E_HS} + T_{\rm A}$$
(7)

The thermal network after bond wire lift-off is shown in Figure 3b. The thermal resistance of the module and equivalent thermal resistance of heatsink stay the same after bond wire lift-off; only part of the bond wire power loss transfers through the die to the heatsink.

Previous research [24,25] proposed that the heat flow in the IGBT module is only affected by the structure after solder fatigue. Although the power loss of bond wires increases, the heat flow stays the same after lift-off due to the same structure. Hence, the equivalent thermal resistance of heatsink on the case point could be calculated based on the same Equation as (3) as in Equation (8).

$$Z_{\rm E_{HS}} = \frac{(T_{\rm C}' - T_{\rm A})}{P_{\rm D} + P_{\rm WB \ D}}$$
(8)

Although the power loss of die P_D and part of the bond wire power loss P_{WB-D} transfer through the die to the heatsink, the power loss of the whole IGBT module P_{IGBT} is measured as the calculated power loss, which is different from the theoretical power loss P'_{loss} on the case point, as shown in Figure 4. Hence, using the power loss of the whole module will overestimate the power loss on the case point, which is higher than the theoretical power loss P'_{loss} , as in Equation (9).

$$P_{\rm IGBT} = P_{\rm D} + P_{\rm WB} = P_{\rm D} + P_{\rm WB_D} + P_{\rm WB_E} = P_{\rm loss}' + P_{\rm WB_E}$$
(9)



Figure 4. Power loss of IGBT module.

Using the overestimated power loss to calculate the thermal resistance of heatsink will underestimate the measured thermal resistance of heatsink Z_{M-HS} on the case point after bond wire lift-off, as in Equation (10).

$$Z_{M_HS} = \frac{T'_{C} - T_{A}}{P_{D} + P_{WB}} = \frac{(P_{D} + P_{WB_D}) \cdot Z_{E_HS}}{P_{D} + P_{WB_D} + P_{WB_E}} < \frac{(P_{D} + P_{WB_D}) \cdot Z_{E_HS}}{P_{D} + P_{WB_D}} = Z_{E_HS}$$
(10)

2.2. Fault Detection Method of IGBT Bond Wire Fatigue Based on Heatsink Thermal Resistance

Both solder fatigue and bond wire lift-off will lead to increases in on-state voltage V_{CE} , power loss P_{loss} , junction temperature T_{J} , and case temperature T_{C} . The thermal impedance of the heatsink increases slightly [25] or remains the same [26] after solder fatigue. However, we propose that, unlike the healthy and solder fatigue modules, the

measured heatsink thermal resistance would decrease after bond wire lift-off, as shown in Table 1. Hence, using the decrement in heatsink thermal resistance can easily distinguish the bond wire lift-off from the healthy module and solder fatigue module. To determine the status of bond wires, a method based on the reduction in heatsink thermal resistance is presented.

Table 1. Different performance of healthy and fatigue modules.

Parameters	Healthy	Solder Fatigue	Bond Wire Lift-Off
V _{CE}	stay	Increase ↑	Increase ↑
P_{loss}	stay	Increase ↑	Increase ↑
$T_{\rm C}$	stay	Increase ↑	Increase ↑
T_{J}	stay	Increase ↑	Increase ↑
Z _{M_HS}	stay	Increase \uparrow or unchanged-	Decrease ↓

The initial thermal resistance of heatsink $Z_{\text{HS}_initial}$ is measured through the power loss of the IGBT module P_{IGBT} and the temperature difference ΔT_{CA} between case and ambient temperature on the case point, as in Equation (11). The $Z_{\text{HS}_initial}$ is set as the reference value of the healthy module.

$$Z_{\text{HS_initial}} = \frac{\Delta T_{\text{CA}}}{P_{\text{IGBT}}} \tag{11}$$

The compared heatsink thermal resistance Z_{HS_K} is measured at the same current level with new power loss P'_{IGBT} and temperature difference $\Delta T'_{\text{CA}}$, as in Equation (12).

$$Z_{\text{HS}_K} = \frac{\Delta T'_{\text{CA}}}{P'_{\text{IGBT}}}$$
(12)

The aging ratio K is defined to detect bond wire fatigue as in Equation (13), which is solely related to the difference between power loss of the whole module and theoretical power loss on the case point.

$$K = \frac{Z_{\text{HS}_K} - Z_{\text{HS}_inital}}{Z_{\text{HS}_inital}} \cdot 100\%$$
(13)

The value of *K* decreases after bond wire lift-off. The number of remaining bond wires will be updated after *K* decreases. The aged IGBT should be replaced to avoid open-circuit failure when the critical failure is reached. The flowchart of the proposed method is shown in Figure 5.



Figure 5. Flowchart of the fault detection method of bond wires.

The proposed method is capable of monitoring the bond wire lift-off by measuring the decrement in heatsink thermal resistance. This decrement occurs in the IGBT operation due to the different heat spreading paths of bond wires. The key advantage of this method is that the thermal resistance of the heatsink is measured independent of working conditions, and does not depend on the current, die temperature, or solder fatigue.

3. Simulation Validation

3.1. Electro-Thermal Modeling for IGBT Module

A multi-physics field finite element method (FEM) model was established based on a 1200 V/50 silicon IGBT module (STARPOWER, Jiaxing, China, GD50HFL120C1). The unpacked power module free of gel is shown in Figure 6a. The geometry of the IGBT layout was supplied by the power module manufacture STARPOWER, shown in Figure 6b. The FEM model is tested with and without bond wires removed. The simulation module is used to show the mechanisms of heat transfer after bond wire lift-off.



Figure 6. (a) IGBT module GD50HFL120C1. (b) Dimensions of GD50HFL120C1.

The bond wires of diode and gate have been removed in the FEM model. The structure and boundaries of the FEM model are shown in Figure 7a. The boundary conditions are set as follows. The ambient temperature is set at 20 °C. All of the boundaries' conditions are set as electric insulation in the physical field of electric currents, except a DC source with a high potential on the collector side and ground potential on the emitter side. A convection coefficient of 3000 W/m²·K is defined on the bottom surface of the baseplate to simulate a wind-cooling heatsink; the rest of the surfaces are set as 12.5 W/m²·K for free convection air in the physical field of heat transfer in solids. The physical fields of heat transfer in solids and electric currents are defined as the source and destination in the multi-physics field of temperature coupling, respectively. All domains are used in electromagnetic heat source and boundary electromagnetic heat source, where the electric currents are set as the electromagnetic source and heat transfer in solids is set as the heat transfer source.



Figure 7. (a) FEM model; (b) meshed IGBT module; (c) mesh of baseplate.

The meshed model is shown in Figure 7b, which consists of 1,152,643 domain elements, 216,192 boundary elements, and 7236 edge elements. To study the effect of bond wire lift-off on the thermal resistance measurement, the bottom of the baseplate layer meshed with more free triangular distribution than other areas as in Figure 7c, which consist of 164,632 boundary elements and 1619 edge elements.

The material properties of the FEM model are shown in Table 2. The conduct characteristic of IGBT die r_{die} is temperature-dependent in different current levels. Hence, the electrical conductivity of die σ_{die} could be obtained based on the die temperature [27], where *l* and *A* are the height and conduct area of IGBT die as in Equations (14) and (15).

$$r_{\rm die} = \frac{V_{\rm CE_25}}{I_{\rm C}} + \frac{V_{\rm CE_150} - V_{\rm CE_25}}{I_{\rm C} \cdot (150 - 25)} (T_{\rm J} - 25)$$
(14)

$$\sigma_{\rm die} = \frac{1}{r_{\rm die}} \cdot \frac{l}{A} \tag{15}$$

Table 2. Material properties of the FEM model.

Part	Material	Density kg/m ³	Electrical Conductivity S/m	Thermal Conductivity W/(m⋅K)
Bond wires	Aluminum	2700	$2.8 imes 10^7$	237.2
IGBT/Diode	Silicon	2329	$\sigma(T_{\rm L}, I_{\rm C})$	124
Solder	96.5Sn3.5Ag	7400	9.1×10^{6}	54
Baseplate	Copper	8960	$6 imes 10^7$	380
Insulation	Ceramic	3780	$1 imes 10^{-6}$	30

This IGBT die shows different temperature characteristics under each current condition, with a negative temperature coefficient (NTC) at 10 A, a zero temperature coefficient (ZTC) at 20 A, and a positive temperature coefficient (PTC) at 30 A and 40 A, as shown in Figure 8a. The decrement in the measured heatsink thermal resistance is determined by the fatigue of bond wires, which is not affected by the conducted current. Hence, the simulation will be tested under each current level. The case temperature is measured by the point below the center of the die on the baseplate, as in Figure 8b.



Figure 8. (a) Temperature characteristics of IGBT electrical conductivity under different current levels; (b) case temperature measure point.

3.2. FEM Results

Figure 9a shows the power loss after bond wires are removed under different current conditions, where the dashed columns are die power loss and solid columns are bond wire power loss. The power loss of the whole module increases due to the bond wire power loss

after lift-off. The power loss of the die stays almost the same, while the power loss of the bond wires significantly increases after lift-off. The power loss of bond wires rises from 0.19 W to 0.79 W at 10 A, while the die power loss stays at 11.16 W. The higher current shows a higher power loss increase in wires, which rises from 3.1 W to 12.6 W at 40 A, while the die power loss remains at 69 W. The case temperature variation is shown in Figure 9b, which shows a slight rise after bond wires are removed due to the increased power loss.



Figure 9. FEM results. (a) Power loss of IGBT module; (b) case temperature at case point.

Not only the power loss but also the proportion of bond wires to total power loss increase after bond wire lift-off, as shown in Table 3. The proportion of bond wires in total power loss rises after lift-off, increasing from 1.7% to 6.59% at 10 A, 2.83% to 10.59% at 20 A, 3.65% to 13.34% at 30 A, and 4.3% to 15.42% at 40 A. The proportion of bond wire power loss to whole power loss of the IGBT module changed obviously after lift-off at a larger current due to the lower on-state resistance of IGBT die.

Table 3. Proportion of bond wire power loss in total loss.

Conduct Current	0 Wire Removed	1 Wire Removed	2 Wires Removed	3 Wires Removed
10 A	1.71%	2.31%	3.49%	6.59%
20 A	2.83%	3.82%	5.72%	10.59%
30 A	3.65%	4.91%	7.31%	13.34%
40 A	4.30%	5.77%	8.55%	15.42%

The measured thermal resistances of heatsink after bond wires were removed are shown in Figure 10a. Although the thermal resistances show different initial values at each current level due to the spreading of thermal resistance [28], they all decrease after bond

wires are removed. The thermal resistance decreases from 0.357, 7 K/W to 0.353, 2 K/W at 10 A, 0.357, 3 K/W to 0.350, 1 K/W at 20 A, 0.357, 1 K/W to 0.348, 0 K/W at 30 A, and 0.356, 9 K/W to 0.346, 3 K/W at 40 A after bond wires are removed.

The aging ratio *K* of simulation results are shown in Figure 10b. Although the aging ratio shows similar values in each current level, the decrement is more significant at a higher current. The value of *K* reaches 1.27%, 2.02% 2.56%, and 2.96% at each current level with one bond wire remaining. According to the results, the value of *K* decreases after bond wire lift-off. Hence, the decrement in *K* could indicate the fatigue of bond wires to avoid an open circuit.

The heat flow in the IGBT module before and after bond wires are removed is shown in Figure 11. The distribution of heat flow is mainly concentrated under the die before bond wires are removed, while the heat flow of bond wires is nearly negligible. Although the heat flow under the chip stays nearly the same after bond wire lift-off (blue lines), the heat flow of bond wires changes. Bond wire fatigue leads to a rise in bond wire power loss, and heat mainly concentrates in the die side and emitter side. This increase in the heat flow in the emitter side shows that part of the bond wire power loss did not transfer through the die side (red lines). Hence, using the power loss of the whole module to calculate the heatsink thermal resistance will underestimate the result.



Figure 10. FEM results. (a) Heatsink thermal resistance Z_{M-HS} ; (b) aging ratio *K*.



Figure 11. Heat flow in IGBT module after bond wires are removed.

4. Experimental Validation

4.1. Test Bench Setup

The main electrical circuit for the test is shown in Figure 12a. The gate voltage was set at 15 V to control the IGBT. A DC source, which varied from 10 A to 40 A with 10 A intervals, was used to emulate the different operating conditions. The collector–emitter voltage was measured by oscilloscopes.

The test environment is shown in Figure 12b. The case temperature was measured from the thermocouple data logger (PICO, Cambridgeshire, UK, TC08). A fan-cooled heatsink (GD Rectifiers, West Sussex, UK, PS260/xxF(6)) was set as the air-cooling heatsink to be tested. Two graves were incised on top of the heatsink to place the thermal couples. The case temperature was measured by the thermal couple, as shown in Figure 12c. A thermal pad was attached to the module baseplate to reduce the air gap between the heatsink and IGBT. To emulate the aging of bond wires, the thermal resistance of heatsink was measured with different bond wires removed. The temperature curve of the case point on heatsink at 30 A is shown in Figure 12d, where the blue solid line is the case temperature, the black dashed line is the ambient temperature, and the red dashed line is the steady temperature of the case point. The forced air-cooling heatsink reaches its steady state after 500 s. Hence, the power loss and case temperature are measured after 10 min until reaching thermal steady state in each test.



Figure 12. Test bench: (**a**) main electrical circuit; (**b**) test environment; (**c**) thermal couples on heatsink; (**d**) temperature curve of case point on heatsink at 30 A.

4.2. Experimental Results Analysis

The experiment results show that the aging of bond wires finally leads to a rise in the power loss of the IGBT module; the module fuses at 40 A with one bond wire remaining, as in Figure 13a. The power loss shows a small rise after bond wire lift-off at the smaller current, which increases more significantly at a higher current level. These increased power losses finally lead to a rise in the temperature at case point, as shown in Figure 13b. The experimental results show that the increase in case temperature is more significant at a higher current, while the variation is small at 10 A due to its low power loss.

The measured heatsink thermal resistances are shown in Figure 13c. Although the initial measured thermal resistance is different for each current level due to the thermal spreading resistance, they all show a decreasing trend after bond wires are removed. The measured thermal resistance decreases from 0.4427 K/W to 0.3960 K/W at 10 A, 0.3803 K/W to 0.3657 K/W at 20 A, and 0.3729 K/W to 0.3548 K/W at 30 A after three bond wires are removed. Although this module fused at 40 A with one wire remaining, it still decreases from 0.3609 K/W to 0.3568 K/W with two wires removed.

Figure 13d illustrates that the value of *K* shows similar decreasing trends at higher currents, and shows a large decrement at 10 A. The aging rate *K* is only dependent on the heat flow of bond wires, which are free of operating conditions. Hence, *K* can be used to detect the fault of bond wires to avoid the open circuit.



Figure 13. Experimental results: (a) power loss of IGBT module; (b) case temperature; (c) heatsink thermal resistance Z_{M-HS} ; (d) aging ratio *K*.

4.3. Discussion

The comparison of bond wire fault detection method is discussed in Table 4. As a non-invasive detection method, the proposed method does not need to change the structure of the IGBT module, which could be used in normal conditions. The case temperature and power loss are easier to measure than the gate signal during operation. Hence, these advantages could help maintain the power converter to avoid an open circuit. However, there are still some problems during measurement.

As previously mentioned, the thermal resistance of heatsink decreases after bond wires are removed. Although the *K* shows a similar reduction at all current levels in the

simulation, it shows an anomalous reduction at 10 A in the experimental results. This strange performance is caused by the measurement of the case temperature.

JESD51-1 [29] proposed to measure an accurate thermal resistance with at least a 20 °C temperature rise on-die, because the high power loss of die could make the detection of the case temperature more accurate. The increased power loss after bond wires are removed is shown in Figure 14. The experimental results show that power loss significantly increases at higher current levels after bond wires are removed, while the increased power loss at 10 A is far smaller than other current levels.

The small increase in power loss at 10 A makes it difficult to detect the variation in case temperature after lift-off, which causes a small change in the case temperature of less than 0.1 °C. These small changes in the case temperature lead to inaccurate measured results, shown in Figure 13d. The low power loss makes it difficult to detect the case temperature variation after bond wires are removed at a low current, while this is easier to detect at a higher current. Thus, it is important to ensure the sensitivity of the case temperature detection method to provide accurate measurement results, which would be better to use in higher current working conditions.

Table 4. Comparisons of bond wire fault detection.

Det	ection Type	Measured Parameter	Working Conditions	Reference
Invasive	Added layout	Voltage	Normal condition	[8]
Detection Method	Current sensor	Current	Normal condition	[9–11]
	Gate charging current	Gate signal	Normal condition	[12]
	Gate charging time	Gate signal	Special gate driver	[13]
	Transconductance	Gate signal	Normal condition	[14]
X T T .	Stray inductance	Gate signal	Normal condition	[15]
Non-Invasive Detection Method	Conduct voltage at the inflected point with special gate voltage	Conduct voltage	Special conduct current at a special gate voltage	[17–19]
	Short-circuit current with special gate voltage	Current	Short-circuit at a special gate voltage	[20]
	Measured thermal resistance of heatsink	Thermal resistance	Normal condition	This paper



Figure 14. The growth of the IGBT module's power loss after bond wires are removed.

5. Thermal Resistance Measurement of Heatsink in Power Cycling

To verify the detection method proposed in this paper, a power cycling test is used to simulate the power converter. The power cycling circuit is shown in Figure 15. A single-phase full-bridge is built based on Ref. [30], which could generate a high-temperature swing with low power loss due to the inductive load. The power cycling circuit is shown

in Figure 16. The full-bridge is composed of IGBT1, IGBT2, IGBT3, and the device under test (DUT). The V_{CE} is measured by the V_{CE} measurement circuit. A small current source (100 mA) is used to measure the junction temperature of IGBT by the V_{CE} measurement circuit with the Temperature-Sensitive Parameter (TSEP) method. The auxiliary IGBT is used to block the branch of DUT during junction temperature measurement.

The test bench is shown in Figure 16. To show the feasibility of the proposed method, a different IGBT module (Semikron, Zhuhai, China, SKM50GB12T4) was used for this experiment. The DC source was set at 50 V and a 0.02 mH inductor was used as the load. The gate source and clamp source supply the gate driver and V_{CE} measurement circuit. The IGBT was controlled by DSP. All of the data were collected by the NI DAQ. The control signal and acquisition signal were processed by LabVIEW on computer. The IGBT was placed on the cold plate and cooled by the chiller. The DUT was tested with a temperature variation of 83.2 °C and mean die temperature of 93.3 °C. The working frequency and switching frequency were 0.03 Hz and 6 k Hz, respectively.

The DUT failed after 56,879 cycles. The open package of the failed IGBT module is shown in Figure 17a. There are five failed wires on the chip with one wire remaining in Figure 17b.



Figure 15. Power cycling circuit.



Figure 16. Test bench.

Previous research proposed that the thermal resistance will decrease after bond wires failed [23], which is shown in Figure 18a, where the brown wave is normalized conduct voltage and the blue wave is normalized measured thermal resistance of the IGBT module. The measured thermal resistance of the IGBT module could be measured in this test due to the special custom circuit test circuit; however, it is nearly impossible to measure the thermal resistance of the module during operation in a normal power converter. Although the measured thermal resistance of heatsink seems to show a notable change during cycling, it shows a significant decrease after bond wires fault, which is shown in Figure 18b, where the brown wave is normalized conduct voltage and the blue wave is normalized measured thermal resistance of heatsink.



(a)

(b)





Figure 18. Normalized measured results of (a) IGBT module and (b) heatsink.

All in all, these results show that the measured thermal resistance of heatsink is easy to obtain to indicate the bond wire fault of IGBT modules, which might be helpful for the condition monitoring of power converters.

6. Conclusions

We proposed a novel method to detect bond wire fatigue by the decrement in measured heatsink thermal resistance. The advantage of this method is that it is not necessary to detect junction temperature, and thus, it could be used in normal working conditions. A multi-physics field FEM model was established to validate this method. The simulation results show that the heat flow changes after bond wire lift-off, which overestimates the calculated power loss and underestimates the measured heatsink thermal. Hence, the decrement in measured thermal resistance of heatsink could be used to detect the fatigue of bond wires. This method was verified by our experimental results. A power cycling

test was used to show the variation in measured thermal resistance of heatsink during the aging process of the IGBT module, which verified the fault detection method.

The scope of this paper is monitoring the fatigue of bond wires under normal operation conditions, which could provide information for health management to avoid open-circuit faults. However, it is still difficult to measure the state of IGBT in the power converter. In future work, this method will be further studied to be integrated into a real power converter, which could help to ensure the reliable operation of the converter.

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