Comparison between the influence of mechanical vibration and junction temperature rise originated bond wires detachment on the characteristics of IGBT module

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Abstract. As the main device in a power system, the IGBT module works in the frequent power cycle for a long time, resulting to the fluctuation of junction temperature and heavy mechanical stress loading. These two factors threaten the reliability of bond wires and the IGBT module significantly. This study aimed at improving the reliability of the semiconductor device. IGBT dual bridge module was used as the primary research object, establishing the relationship between the bond wires detachment and resistance. MATLAB was used for mathematical analysis to determine the quantitative influence of the two conditions on several static characteristics of the IGBT module. Our study provides more samples and references to monitoring the IGBT bond wires and demonstrates the difference and similarity of these two factors.

1. Introduction

IGBT (Insulated Gate Bipolar Transistor) combined with BJT (Bipolar Junction Transistor) and MOSFET (Metal Oxide Semiconductor Field Effect Transistor), is one of the most widely used semiconductor power devices in aerospace, power grid, rail transportation and other fields as a core device for controlling and converting electrical power. Until now, IGBT has developed to the sixth generation. Its smaller chip size and higher voltage withstanding ability makes it frequently used in high temperature and high-power occasions [1]. Several different materials combine with the IGBT modules and they are assembled using different techniques, such as wire bond, soldering, DBC (direct bond copper) and pressure contact interconnect technique in the packaging manufacturing process. Wire bond lift-off and bond heel cracking are considered as essential factors in power electronic module reliability. Two primary reasons account for the failure of the wire bond. Firstly, it is due to the mismatch in the CTE (coefficients of thermal expansion) between the wire and substrate material [2]. In this case, the cyclic occurring thermo-mechanical loads lead to crack propagation in the wire material slightly above the metallization layer [3]. The other reason is due to the mechanical collision, for example, in motor cars. IGBT modules are often utilized in transportation, and frequent collisions cause root bonds of IGBT modules to fall off or break [4]. According a study, 55 % of the bond wire failure could be attributed to temperature rise and 35 % to mechanical stress [5]. The most inherent difference between the two situations is that mechanical vibration does not cause the change in
temperature; in other words, it only increases the resistance of the bond wires. However, when the
dunction temperature increases, the working condition of the IGBT and FWD (Free Wheeling Diode)
also changes.

For instance, the static parameters like on-resistance and saturation voltage can reflect the working
conditions of IGBT modules. Specifically, when the on-resistance or the saturation voltage of IGBT
modules increase by 20% and 5% respectively, it can be considered that the module has failed [6].

Given the current research status, all research on IGBT bond wires are focused on the bond wires in
a specific place [7-9], and there is no classification of the types of wires.

Therefore, this study seeks to establish the relationship between the static parameters and the
condition of the bond wires. The on-resistance and saturation voltage of the IGBT can be
quantitatively calculated when there are varied numbers of bond wire sheds at different positions due
to the two cases, providing references for IGBT module monitoring. The specific failure of the
different number of bond wires in a different position to the IGBT modules will be analyzed, which
can help in the deduction of the working condition of the IGBT modules by monitoring the bond wires
and demonstrating the similarities and differences between the two cases.

2. Model establishment and analysis process

2.1. Model establishment

![Figure 1. FF300R12KS4 IGBT module bonding wires classification and equivalent circuit diagram.](image)

With respect to the module used for researching, IGBT dual bridge module (FF300R12KS4) is
selected due to its highly symmetrical structure. The classification of the IGBT’s bond wires and its
equivalent circuit are shown in figure 1. R1, R2, R3 are the equivalent resistances of the
collector-emitter bond wires, full-bridge bond wires, IGBT chip unit (including the IGBT and FWD,
and the bond wire and capacitor between them), and R41 and R42 are half-bridge bond wires.

The research environment of the bond wires detachment due to mechanical vibration was
performed under standard temperature, 25 °C. For the bond wire’s detachment caused by changing
temperature, when the junction temperature change is less than 80 °C, the primary failure of the IGBT
is solder layer failure. Likewise, when the increase in junction temperature is greater than 100 °C,
bond wire failure occurs [10]. Therefore, suppose the detachment of the bond wires happens when the
junction temperature rises to 100 °C, then, a temperature of 125 °C will be selected as the junction
temperature of this module.
2.2. Analysis process

Table 1. Parameters of each bonding wire at 25℃.

| Material | Length | Diameter | Number | Resistivity | Resistance of each wire(Ω) |
|----------|--------|----------|--------|-------------|---------------------------|
| R1       | Aluminum | 0.025m  | 80 μm | 9           | 2.83x10^{-8}   | 0.00624                  |
| R2       | Aluminum | 0.015m  | 80 μm | 8           | 2.83x10^{-8}   | 0.00377                  |
| R3       | Aluminum | 0.015m  | 80 μm | 8           | 2.83x10^{-8}   | 0.00377                  |
| R4       | Aluminum | 0.015m  | 80 μm | 8           | 2.83x10^{-8}   | 0.00377                  |

Firstly, getting the parameters of different kinds of wires by checking to the official manual and measuring its physical characteristic in the different environment. The material parameters of bond wires under 25℃ and 125℃ are shown in Table 1 and Table 2 respectively.

Table 2. Parameters of each bonding wire at 125℃.

| Material | Length | Diameter | Number | Resistivity | Resistance of each wire(Ω) |
|----------|--------|----------|--------|-------------|---------------------------|
| R1       | Aluminum | 0.025m  | 80 μm | 9           | 4.11x10^{-8}   | 0.00899                  |
| R2       | Aluminum | 0.015m  | 80 μm | 8           | 4.11x10^{-8}   | 0.00543                  |
| R3       | Aluminum | 0.015m  | 80 μm | 8           | 4.11x10^{-8}   | 0.00543                  |
| R4       | Aluminum | 0.015m  | 80 μm | 8           | 4.11x10^{-8}   | 0.00543                  |

It is possible to get the resistance of each wire according to the data in Table 1 and Table 2. The internal wires connecting form is parallel, thus, the resistance of R1,R2,R41,R42 is available by a simple formula:

$$R_n = \frac{R}{N}$$  \hspace{1cm} (1)

If there are x bond wires detached at this position, the equivalent resistance of the corresponding bond wires is

$$R_n = \frac{R}{N-x}$$  \hspace{1cm} (2)

Besides, the relationship between the on-resistance of the IGBT module and the local resistance can be obtained by Figure 1, the detailed relationship is:

$$R_{on} = 2R_1 + (2R_3 + R_{41})/(2R_2 + 2R_3 + R_{42})$$

$$= 2R_1 + \frac{4R_3R_5 + 4R_3^2 + 2R_3R_{41} + 2R_3R_{41} + 2R_3R_{41} + R_{41}R_{42}}{4R_3 + 2R_2 + R_{41} + R_{42}}$$  \hspace{1cm} (3)

From the official product manual, we can get the on-resistance of the IGBT module in 25℃ and 125℃ environment when it is working normally, which means the detachment of bond wires have not happened. When bond wires are broken in different places, the on-resistance of the module will change in different degree because the increase of the local resistance (R1,R2,R41,R42). But the value of R3 cannot be measured directly in that the U-I curve of IGBT chip is not linear. Therefore, we have to calculate it indirectly by formula (3), the value of R3 under different voltage are illustrated in Table 3 and Table 4.
Table 3. Data of IGBT unit resistance (R3) under 25℃.

| V_{ce} (v) | R3 (Ω) |
|------------|--------|
| 0-0.6      | ∞      |
| 1          | 0.0218 |
| 1.5        | 0.0105 |
| 2          | 0.0065 |
| 3          | 0.0046 |
| 3.5        | 0.0027 |
| 4          | 0.0027 |
| 4.5        | 0.0027 |

Table 4. Data of IGBT unit resistance (R3) under 125℃.

| V_{ce} (v) | R3 (Ω) |
|------------|--------|
| 0-0.6      | ∞      |
| 1          | 0.0301 |
| 1.5        | 0.0155 |
| 2          | 0.0099 |
| 3          | 0.0070 |
| 3.2        | 0.0051 |
| 3.5        | 0.0046 |
| 4          | 0.0032 |
| 4.5        | 0.0032 |
| 5          | 0.0032 |
| 5.5        | 0.0032 |

From the tables and formulas, when different number of wires are broken in different places, its quantitative effect on the on-resistance of IGBT module can be solved. We can also obtain the change of the V_{CE}-I_{C} characteristic curve and the saturation voltage of the IGBT module at this time by the change of on-resistance. The derivative of the V_{CE}-I_{C} curve is equal to the on-resistance and the saturation voltage is corresponding to a specific collector current. The V_{CE}-I_{C} curve and the definition of this type of IGBT module can be obtained in its product manual.

3. Results and discussion

3.1. Similarities and differences of effect on the IGBT module’s on-resistance caused by the two situations

The on-resistance of the IGBT module corresponding to the bond wire failure caused by the mechanical vibration and the increase in junction temperature can be obtained after quantitative calculation using MATLAB according to the above process. The module’s on-resistance increase rate caused by the two situations is shown in Figure 2.
Figure 2. IGBT module’s on-resistance increases rates caused by the two situations.

Figure 2 shows that the rate of change of the IGBT’s on-resistance in both cases increases with the number of broken bond wires, and when the number of failures is higher, the more obvious the increasing trend. Also, although the effect of the two situations of the IGBT module is different, the degree of influence of the same type of bond wires in the two situations is the same. The influence of detachment of collector and emitter bond wires ($R_1$) is the largest, the half-bridge bond wires ($R_{41}$) is next, and the full-bridge bond line ($R_2$) is the smallest.

However, the effect of the bond wire failure caused by the increase in junction temperature (100 °C) on the on-resistance is much greater than that caused by mechanical vibration. Specifically, when the bond wire failure occurs at any position due to the increase in junction temperature, it will cause the on-resistance of the IGBT to increase at least by 30 %, when only one wire detaches, the on-resistance ascend from 0.0045 Ω to 0.0059 Ω.

Concerning the bond wire detachment caused by mechanical vibration, only the collector and emitter bond wires break more than six (6) or all of the full-bridge or half-bridge bond wires fall off. The module resistance will increase by more than 30 %. According to Reference [6], when the on-resistance of the IGBT module increases by more than 20 %, the module can be regarded as a failure. Hence, when the junction temperature increases by 100 °C, the entire module is considered to have failed. For the wires whose detachment was caused by mechanical vibration, when the collector and emitter bond wire breakage ratio is less than 60 %, the bond wires between half-bridges and full-bridges are less than seven (7) and eight (8) respectively, and the module still works normally.

The reason for these differences is mainly due to the increased resistance of the bond wires, the IGBT chips, and the FWD chips. By comparing Figure 2, when the junction temperature increases to 100 °C, the resistance of bond wires in the collector-emitter, between the half-bridge and full-bridge increases by 44 %. Furthermore, according to the comparison between Table 2 and Table 3, the IGBT unit’s resistance increases by 19 %. In contrast, when the IGBT module works under 125 °C, and a wire breaks, the on-resistance of the module increases by only 2 % compared with the normal conditions, which illustrates that the detachment of the bond wires is not the primary reason for the failure of the module. However, it is caused by the rise of the resistance of the wires and chips.
3.2. The Similarities and differences of effect on the IGBT module’s output characteristic and saturation voltage caused by the two situations
Firstly, the relationship between the collector current $I_C$ and the number of bond wires crack at different positions, was calculated, and the corresponding output characteristic curve was drawn. The $I_C$-$V_{CE}$ characteristic curves corresponding to the mechanical vibration and junction temperature rise are shown in Figure 3 and Figure 4, respectively.

![Figure 3](image1)

**Figure 3.** The output characteristic of IGBT modules when bonding wires fall of because of mechanical vibration.

![Figure 4](image2)

**Figure 4.** The output characteristic of IGBT modules when bonding wires fall of because of the rise of the junction temperature.

As shown in Figures 3 and 4 respectively, the crack of the collector-emitter bond wires in both cases has the most significant impact on the output characteristics of the IGBT, and the corresponding collector current at the same collector-emitter voltage decreases significantly. In both cases, when breaking 1-4 wires, the output characteristic curve is the same. Only five (5) or more collector-emitter wires and all of the bridge bonding wires, when detached, will lead to the failure of the module.
In contrast, when the junction temperature rose, the effect on the output characteristics was more significant. As Figure 4 shows, compared with the IGBT module working under normal junction temperature, junction temperature rise caused a significant change in the output characteristic curve. The specific performance is that the switching time becomes prolonged, and the time to reach the Miller platform also becomes significantly longer. When the bond wire fails due to mechanical vibration, unless more than five (5) wires are cracked in the collector-emitter bond wire, or the bond wire between the full-bridge and the half-bridge fail, otherwise the output characteristic curve will not change significantly.

Table 5. The saturation voltage of IGBT modules when wires fall off because of mechanical vibration.

| Broken wires at R1 | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|--------------------|---|---|---|---|---|---|---|---|---|---|
| Vcesat(v)          | 3.136 | 3.147 | 3.171 | 3.206 | 3.260 | 3.319 | 3.420 | 3.706 | ∞  |
| Rise ratio(%)      | 0 | 0.4 | 1.1 | 2.2 | 4.0 | 5.8 | 9.1 | 18.2 | 42.7 | ∞  |

| Broken wires at R2 | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------------------|---|---|---|---|---|---|---|---|---|
| Vcesat(v)          | 3.136 | 3.143 | 3.144 | 3.145 | 3.147 | 3.160 | 3.207 | 3.276 | 4.058 |
| Rise ratio(%)      | 0 | 0.2 | 0.3 | 0.3 | 0.4 | 0.8 | 2.3 | 4.5 | 29.4 |

In contrast, when the junction temperature rose, the effect on the output characteristics was more significant. As Figure 4 shows, compared with the IGBT module working under normal junction temperature, junction temperature rise caused a significant change in the output characteristic curve. The specific performance is that the switching time becomes prolonged, and the time to reach the Miller platform also becomes significantly longer. When the bond wire fails due to mechanical vibration, unless more than five (5) wires are cracked in the collector-emitter bond wire, or the bond wire between the full-bridge and the half-bridge fail, otherwise the output characteristic curve will not change significantly.

Table 6. The Saturation voltage of IGBT modules when wires fall off because of junction temperature increase.

| Broken wires at R1 | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|--------------------|---|---|---|---|---|---|---|---|---|---|
| Vcesat(v)          | 3.136 | 3.850 | 3.883 | 3.933 | 3.993 | 4.100 | 4.264 | 4.367 | 5.750 | ∞  |
| Rise ratio (%)     | 0 | 22.6 | 23.8 | 25.4 | 27.3 | 30.7 | 36.0 | 39.3 | 83.4 | ∞  |

| Broken wires at R2 | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------------------|---|---|---|---|---|---|---|---|---|
| Vcesat(v)          | 3.136 | 3.824 | 3.831 | 3.845 | 3.853 | 3.870 | 3.910 | 4.003 | 4.927 |
| Rise ratio (%)     | 0 | 21.9 | 22.2 | 22.6 | 22.9 | 23.4 | 24.7 | 27.6 | 57.1 |
To accurately evaluate the reliability impact on the IGBT module, the corresponding saturation voltages in these two cases were calculated as shown in Tables 5 and 6. According to literature [6], when the saturation voltage rises by 5 %, the IGBT module can be deemed to have failed. As shown in Table 5, when the mechanical vibration causes more than five (5) collector-emitter bond wires and more than seven (7) half-bridge and all full-bridge bond wires break, the IGBT module will fail. However, according to Table 6, it can be demonstrated that when the junction temperature increases to make the bond wires crack, no matter what kind of cracking occurs in the bond wire, the saturation voltage increase rate is more than 20 %, which means the module suffers from severe failure.

4. Conclusions
As the paper shown, the main difference between bond wire failure caused by mechanical vibration and thermal stress is whether the junction temperature of the IGBT module has changed. Mechanical stress will only cause the bond wires to crack, but the increased temperature will change the operation state and the parameters of other parts like the IGBT chips and the FWD chips as well.

The results obtained proved that the failure of the bond wire in both cases caused the increase of the on-resistance and the saturation voltage, and their increased rate grew with the number of broken wires. The breaking of the collector and emitter bond wires has tremendous effect on the static parameters of the IGBT module and the reliability of the IGBT module. When mechanical vibration causes wires to fall off more than five (5), the IGBT module is at risk of failure. For the bond wires between the full-bridge -between the half-bridges, a small number of shedding wires has little effect on the reliability of the IGBT module.

In contrast, when the bond wires fail because of the thermal stress caused by the increased junction temperature (100°C), whichever bond wire fails, the entire module is in a state of failure. This is mainly caused by the significant increase in the resistance of the IGBT chips, the FWD chips, and due to changed temperature of bond wires. But the impact of the detachment of the bond wires on the reliability of IGBT module is insignificant.

This project attempts to improve the reliability of the IGBT and semiconductor power device by comparing two different situations that cause the failure of the bond wires. Compared with previous research, the innovation of this project is the analysis of various types of bond wires and the use of an uncomplicated analysis method to summarize a general rule. The lack of experiment lessens on the accuracy of data but the findings demonstrated in this article have a reference significance, which can provide more samples and data for IGBT module bond wire monitoring and junction temperature monitoring.

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