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Study on Case Temperature Distribution for Condition Monitoring of Multidie IGBT Modules

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***Abstract*—The parasitic and proximity effects in multidie insulated-gate bipolar transistor (IGBT) modules lead to nonuniform distributions of junction temperature (T_J) and case temperature (T_C) among different dies. This feature can be used to monitor the operating and health condition of multidie IGBT modules. This paper reports a comprehensive study on the distribution of T_C and its influence on T_J estimation using a thermal network model for a multidie IGBT module before and after aging. Specifically, experimental studies using accelerated aging tests are conducted for a 9-die IGBT module. Results demonstrate that the T_C at the position close to the package side and terminal lead should be used to estimate T_J for condition monitoring of the multidie IGBT module. Moreover, the variation of T_C and nonuniformity of the T_C distribution can be used as indicators for health condition monitoring of the multidie IGBT module.**

I. Introduction

One of the most major failure mechanisms observed in the insulated-gate bipolar transistors (IGBTs) with the traditional direct bond copper (DBC) structure (Fig. 1) is bond wire wear-out, including bond wire lift-off and heel crack. This failure mechanism is caused by mismatch of the coefficients of thermal expansion of different materials in the chip package after long-time power and thermal cycling [1]. Therefore, electrothermal analysis has been commonly applied for condition monitoring [2] and remaining useful life (RUL) prediction of IGBTs based on the Coffin-Mason equation [3].

The junction temperature (T_J) is the most effective indicator to monitoring an IGBT's health and operating conditions and predicting the IGBT's RUL [4], because it reflects the operating state and is affected by most failure mechanisms of IGBTs. The value of T_J should be limited below a certain level, usually 150°C, during the IGBT's operation according to the manufacturer datasheet. As shown in Fig. 1, a modern IGBT module in high-power applications usually contains multiple dies to support high current operation and the values of T_J of different dies are not exactly the same. The nonuniform distribution of T_J originates from the unbalanced current distribution during power cycling, caused by the existence of parasitic inductances and the proximate effect of adjacent bonding wires [5]. Therefore, the highest T_J of these dies should be used for health condition monitoring of the multidie IGBT module. How to obtain the accurate information of T_J in a cost-effective way is an important issue. Because the junctions of modern IGBT modules are not accessible in practice, currently the most economical and feasible way to acquire T_J of an IGBT module is the thermal model-based method [6]. In a thermal model, the case temperature (T_C) on the bottom surface of the baseplate is an important parameter to estimate T_J. Similar to T_J, T_C also has a nonuniform distribution during the IGBT's operation. Therefore, T_C is also a good indicator for condition monitoring of IGBTs.

This paper conducts a study of T_C distribution of a multidie IGBT module before and after aging. Based on the study, the location to obtain the appropriate T_C is determined for T_J estimation for condition monitoring of the multidie IGBT module during its lifetime. Furthermore, this paper proposes to use the variation of T_C and nonuniformity of the T_C distribution as indicators for health condition monitoring of multidie IGBT modules. Experimental results are provided to validate the proposed study.

II. Research Background and Proposed Study

A. Thermal Model

A typical Foster thermal network for IGBTs consists of four pairs of thermal resistances and capacitances (RCs), as shown in Fig. 2, which is applied in this work. The values of the thermal RCs can be obtained from the datasheet provided by the manufacturer [7]. Then the relation between T_J and T_C can be described by the following equation.

$$T_J = T_C + P_{diss} \cdot Z_{th(JC)} \quad (1)$$

where P_{diss} is the power dissipated in the IGBT, and $Z_{th(JC)}$ is the equivalent thermal impedance between the junction and the case of the IGBT, as described in Fig. 2.

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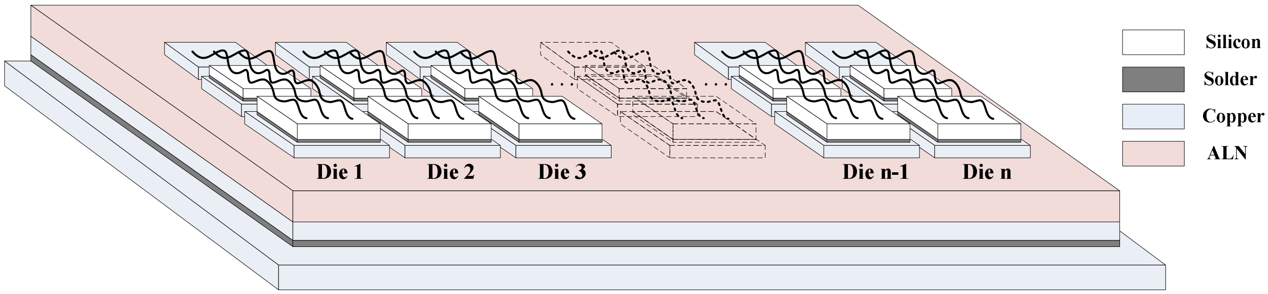

Fig. 1. The DBC structure of a multidie IGBT module.

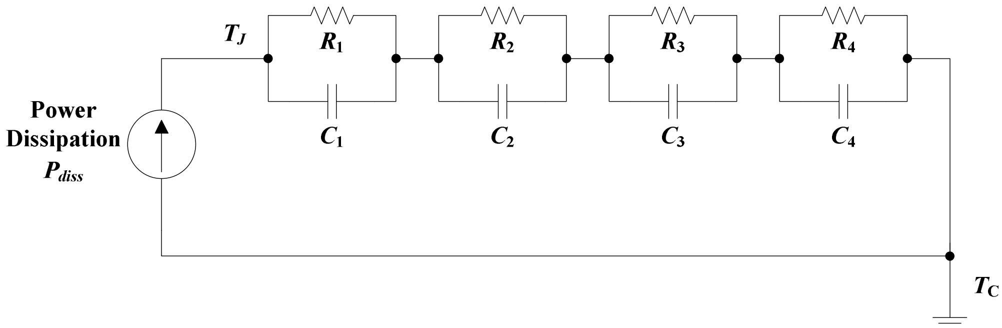

Fig. 2. Schematic of a Foster equivalent RC thermal network for IGBTs.

B. Parasitic Effect

Stray and parasitic inductances are inevitably present in an IGBT module. Prior studies have revealed that the terminal lead inductance dominates the package inductance compared with the parasitic inductances of the IGBT bonding wires, but the layout of the parasitic inductances of an IGBT module leads to an unbalanced current distribution [5], [8] in the IGBT module. Because of the planar layout of the package and a relatively large total-chip-area of a high power module, the parasitic inductances are distributed parameters. Even though the chips are carefully selected and placed in parallel, there are still discrepancies in circuit parameters imposed by the parasitic inductances, which can be identified in the high current loop as well as the gate signal loop. These differences together with the proximity effect result in a nonuniform current distribution and, therefore, uneven power loss among the chips. As a result, the heat generated by the power losses in different dies of the IGBT module is nonuniform, as illustrated in Fig. 3. Consequently, the heat flows from the junction to the baseplate of different dies are nonuniform. This will alter the case temperature distribution on the surface of the baseplate, leading to different values of T_{Cj} (j = 1, 2, ⋯, n) under different dies in Fig. 3. The die close to the package side and terminal lead produces more heat than others and, therefore, will enter the "fatigue stage" earlier than the others. Therefore, the T_C measured under that die should be used to estimate T_J for condition monitoring of the IGBT module. On the other hand, the degree of nonuniformity of the T_C distribution will increase with the development of the device's aging and, therefore, can be used as an indicator for health condition monitoring of the IGBT module. This paper studies the variation of T_C (i.e., ΔT_{Cag}) with time at the same location and the variation of T_C (i.e., ΔT_{Cpo}) at the same time between different locations on the

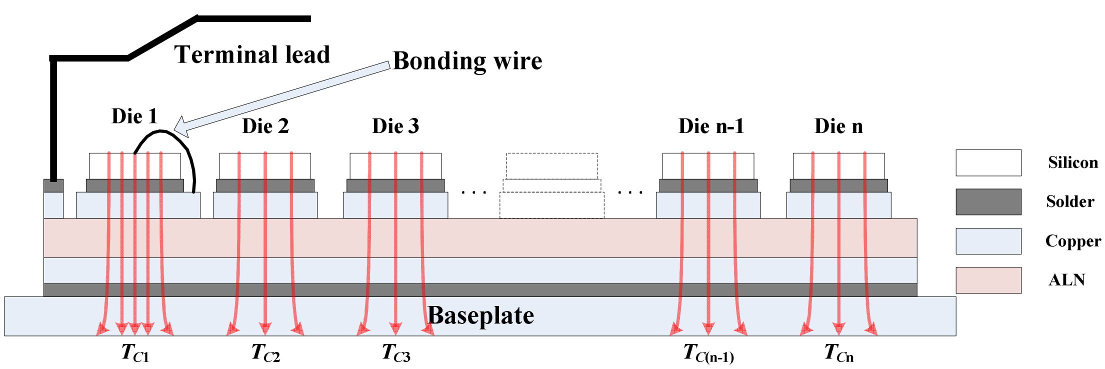

Fig. 3. Heat flows through a multidie IGBT module.

bottom surface of the baseplate of an IGBT module. Experiments are conducted to show that both ΔT_{Cag} and ΔT_{Cpo} can be used as indicators for health condition monitoring of multidie IGBT modules.

III. Experiment

In order to acquire sufficient information of the T_C distribution for an IGBT module in different health conditions, thermo-sensitive electrical parameter (TSEP) test, pulsed-current test, and accelerated aging test are performed for a multidie IGBT module consisting of two IGBT switches, as shown in Fig. 4. The IGBT module has the maximum operating junction temperature of 150 °C specified by the datasheet. Each IGBT switch has nine dies in the chip of the module.

A. TSEP Test

The collector-emitter saturation voltage $V_{CE(sat)}$ is a commonly used TSEP for measuring the T_J of an IGBT module [9]. In this work, the TSEP test is first performed to obtain the real-time relationship between T_J and $V_{CE(sat)}$ using a temperature chamber, a DC source, and an oscilloscope. The test IGBT module is placed in the temperature chamber to be heated at different constant temperature conditions. At each temperature condition, a 1 A current is applied to the test IGBT using the DC source and the $V_{CE(sat)}$ is recorded by the oscilloscope. The use of such a low current limits the self-heating to a negligible value and improves the accuracy of the measurement of T_J. The relationship between T_J and $V_{CE(sat)}$ obtained from the TSEP test is shown in Fig. 5. The resulting T_J is called measured T_J, which is used as a reference to compare with the T_J estimated from the thermal model used in other tests described below.

B. Pulsed-Current Test

Pulsed-current test is performed during different stages of the accelerated aging test of the IGBT module to acquire the measured and estimated T_J. In each test cycle, four 400 A high-current pulses as shown in Fig. 6 are applied to the IGBT module using a programmable 600 A DC source. Each of the first three high-current pulses lasts for one second with a 50% duty ratio. The ON-state of the last high-current pulse lasts for 0.5 second and then the current drops to 1 A for 3 seconds before becoming zero. The $V_{CE(sat)}$ measured at the moment when the 1 A current is applied is used as a TSEP to acquire the measured T_J. The value of V_{CE} is recorded by an oscilloscope during the entire pulsed-current test. Nine thermocouples with an accuracy of ±0.005 °C are placed right below each die on the bottom surface of the baseplate to acquire the case temperature distribution of the test IGBT module, where T_C is recorded by a data acquisition system developed in LabVIEW™.

C. Accelerated Aging Test

In the accelerated aging test, a 15 V constant voltage is applied to the gate of the IGBT module, and power cycles are applied to the IGBT continuously to accelerate the aging of the device. Each power cycle lasts for 10 seconds, which consists of a 400 A ON-state for 2.5 seconds, following by a 1 A ON-state for 1 second and then a 6.5 seconds OFF-state, as shown in Fig. 7. The 400 A current leads to power dissipation in the IGBT. The following 1 A current is used to acquire the junction temperature T_J according to the TSEP method. Monitoring T_J ensures that the device can be operated with T_J close to the maximum value allowed during the aging process without interrupting the test due to overheating of the device. This test design does not use any gate control circuit, which prevents the influence of unexpected gate control failures on the testing results. In the whole test process, it takes approximately 20,000 cycles before the IGBT enters a fatigue stage [10] and approximately 40,000 cycles when the $V_{CE(sat)}$ acquired has increased 15% over its nominal value. In this case the IGBT is considered in severe degradation [11].

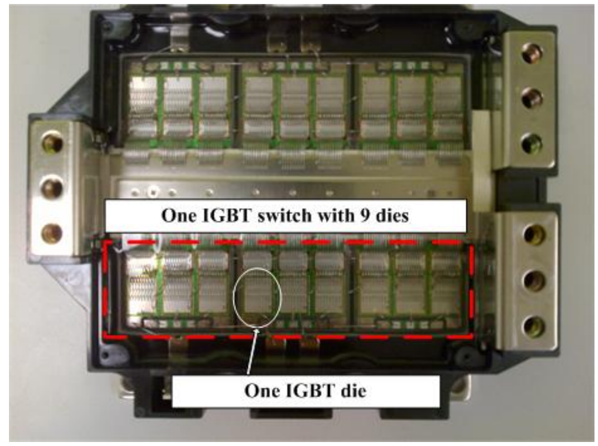

Fig. 4. Internal structure of a test multidie IGBT module.

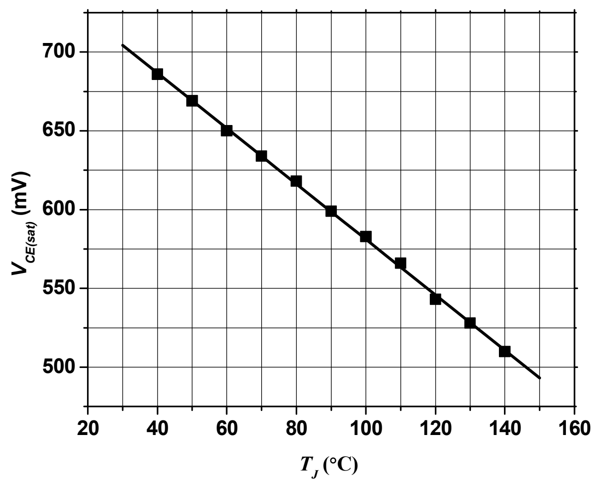

Fig. 5. Measured $V_{CE(sat)}$ as a function of T_J for the test IGBT.

IV. Results and Analysis

Fig. 8 shows the values of T_C measured under the nine dies of the test IGBT when it is operated with I_C = 400 A before and after the accelerated aging test. The test point numbers in Fig. 8 correspond to the dies from left to right of the test IGBT shown in Fig. 4. As expected, before the aging

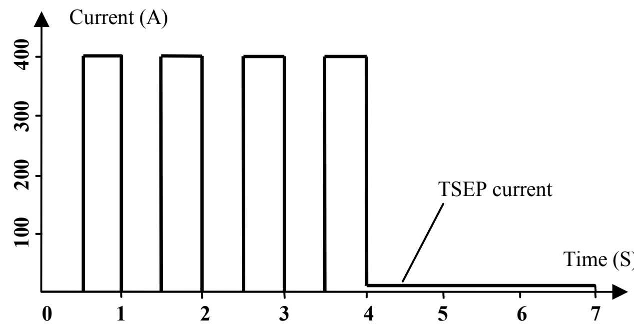

Fig. 6. Pulsed-current waveform used in the tests.

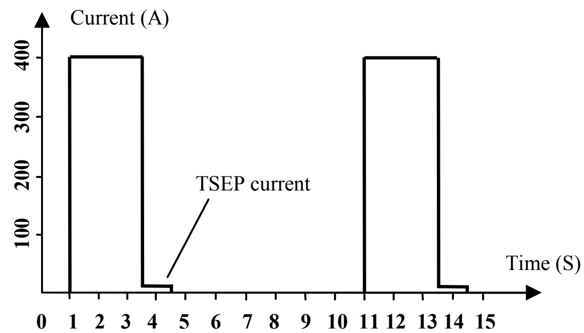

Fig. 7. IGBT current waveform during the aging test.

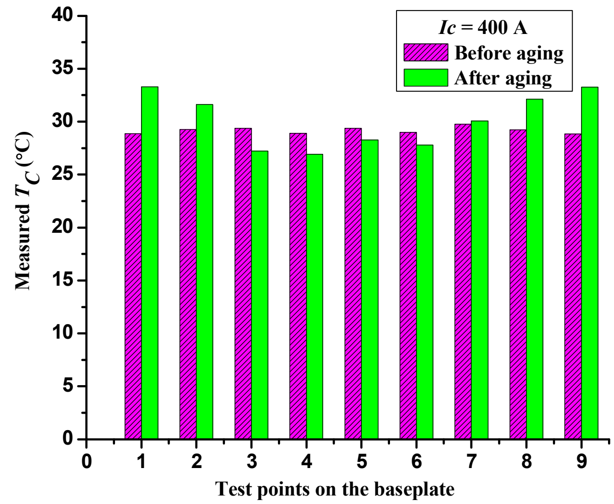

Fig. 8. T_C distribution among nine dies before and after the aging test.

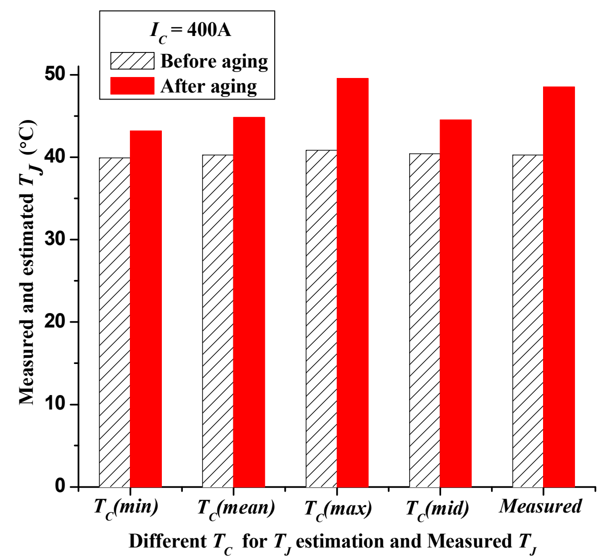

Fig. 9. Comparison of measured T_J and T_J estimated by using different T_C before and after the aging test.

test, the distribution of T_C is almost uniform among different dies; the maximum value of ΔT_{Cpo} among the nine dies is 0.92 °C. However, after the aging test, the nonuniformity of the T_C distribution becomes significant; and the maximum ΔT_{Cpo} increases to 6.37 °C. On the other hand, the largest ΔT_{Cag} before and after aging occurred at the points (dies) close to the package side and terminal lead as predicted. The maximum ΔT_{Cag} is 4.44 °C at the die No. one, and the minimum ΔT_{Cag} is 1.09 °C at the die No. five. This result clearly shows that the degree of nonuniformity of T_C distribution increases remarkably after the IGBT ages, and either ΔT_{Cpo} or ΔT_{Cag}, or the combination of the two parameters can be an effective indicator for health condition monitoring of multidie IGBT modules.

Fig. 9 compares the measured T_J and the values of T_J estimated from the thermal network model by using the minimum [$T_C(min)$], mean [$T_C(mean)$], maximum [$T_C(max)$], and median [$T_C(mid)$] values of T_C from the nine test points before and after the accelerated aging test. Before the aging test, the values of T_J estimated using different T_C have little difference. The maximum error of the estimated T_J with respect to the measured T_J is 0.8% when $T_C(max)$ is used and the minimum error is 0.05% when $T_C(mean)$ is used. It indicates that any T_C can be used to predict T_J before the IGBT ages. However, after the aging test, the heat flows from the junction to the baseplate of different dies are no longer uniformly distributed. The errors of the estimated T_J using different T_C with respect to the measured T_J are larger than those before aging. For example, the minimum error of the estimated T_J with respect to the measured T_J increases to 2.1% when $T_C(max)$ is used, while the error of the T_J estimated from $T_C(mean)$ with respect to the measured T_J increases to 7.7% and the maximum error is 11.1% when $T_C(min)$ is used. As shown in Fig. 6, $T_C(max)$ after aging is obtained from die one, which is close to the package side and terminal lead. Therefore, one thermal sensor can be mounted at this location to estimate T_J for monitoring the operating and healthy conditions of IGBT modules and predicting their RUL during operation.

V. Conclusion

This paper has studied the case temperature distribution of a multidie IGBT module before and after aging. Based on the study, this paper has proposed to use T_C at the locations close to the package side and terminal lead to estimate T_J using a RC thermal network model for condition monitoring and RUL prediction of multidie IGBT modules. Moreover, this paper has proposed to use the variations of T_C, including ΔT_{Cpo}, ΔT_{Cag}, or both as a precursor for health condition monitoring of multidie IGBT modules. Experimental results obtained from the accelerated aging test for 9-die IGBT modules have been provided to validate the proposed study.

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