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Power Cycling Test of Transfer Molded IGBT Modules by Advanced Power Cycler under Different Junction Temperature Swings

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Abstract

In this paper, an effect of junction temperature swings (ΔT_j) on reliability of IGBT modules is studied with 600 V, 30 A, transfer molded power modules. This study is based on power cycling test results of 18 IGBT modules under three different junction temperature swings, namely 40 ˚C, 60 ˚C and 70 ˚C, by means of an advanced power cycler. The advanced power cycler allows performing power cycling tests under similar conditions of IGBT modules in power electronics applications. This paper presents post-failure analysis of the tested IGBT modules of interest in order to investigate the failure mechanism and also to compare results under different ΔT_j. Further, a lifetime factor in respect to ΔT_j is modeled with different lifetime definitions and confidence levels. This paper enables a better understanding of the junction temperature swing-related failure mechanisms and reliability performance of transfer molded IGBT modules for power electronics applications.

1. Introduction

Power cycling test is the major reliability test method of power modules with respect to temperature stress [1]-[3]. By performing this, failure mechanisms of power modules due to temperature stress can be found and thus a weak point of power modules can be improved [4], [5]. Further, new materials and designs for power module packaging can be evaluated [6]. Finally, a lifetime model in respect to temperature stress can be obtained [7], [8]. It is used for lifetime estimation of power modules under mission profiles of power electronic applications [9].

Many power cycling tests have been performed to study an effect of temperature stress on reliability of conventional power modules. However, most of tests have been performed under high temperature swings [5], [10]. There is a lack of study under different temperature swings to compare its failure mechanism and also to obtain a lifetime model including a statistical analysis.

In this paper, the effect of junction temperature swings on reliability of IGBT modules is studied with 600 V, 30 A, 3-phase, transfer molded power modules. This study is based on power cycling test results with 18 samples under three test conditions by an advanced power cycler that allows IGBT module being operated under more realistic electrical conditions of converters. This paper starts with a brief description on the advanced power cycler and test conditions. Then, the results of power cycling tests under three different junction temperature swings are presented. Post-failure analysis results of the tested IGBT modules are also presented. Finally, a lifetime analysis is provided and a relevant lifetime model is developed based on test results.

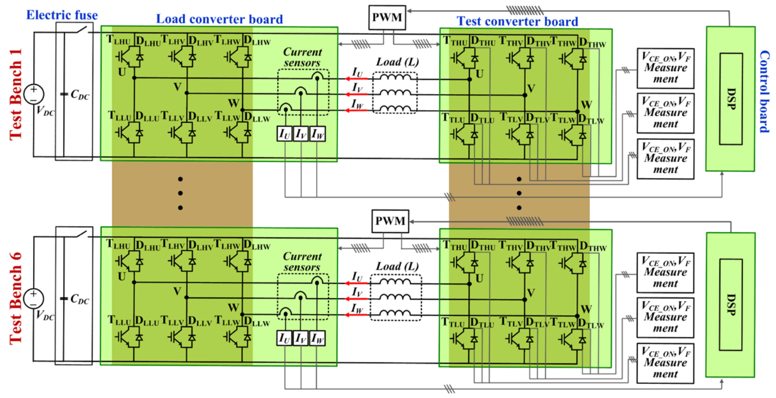

Fig. 1. Schematic of advanced power cycler [12].

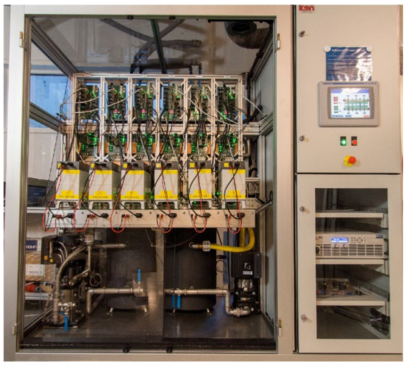

Fig. 3. Prototype of advanced power cycler.

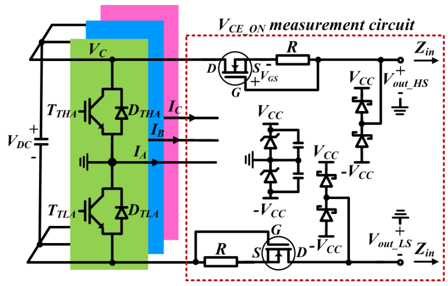

Fig. 2. Real-time V_{CE_ON} and V_F measurement circuit [13].

2. Power Cycling Test by Advanced Power Cycler

2.1. Advanced power cycler

Fig. 1 shows the schematic of the advanced power cycler. It is composed of six test benches, thus six IGBT modules can be tested at the same time. This allows obtaining many test results with reduction of test time for the statistical analysis, which is essential in reliability modelling. Each test bench consists of a test converter board with an IGBT module under test, a load converter board with a load IGBT module and a control board. The test converter and the load converter are mounted on heat-sinks, where the heat-sink temperature for the IGBT module under test is controlled by water cooling systems depending on required test conditions. The heat-sink temperature for the load IGBT module is typically kept as low as possible. Each test bench is operated individually by a separate control system and includes a real-time on-state collector-emitter voltage (V_{CE_ON}) measurement circuit as shown in Fig. 2. It gives benefit when power cycling test is performed because it makes possible to determine the wear-out status of tested IGBT module through V_{CE_ON}. Thus, the power cycling test can be stopped before catastrophic failure occurs in tested IGBT modules.

Table I. Test conditions for the power cycling tests

Cond.	f_{SW} (kHz)	I_{peak} (A)	V_{ref} (V)	T_H (˚C)	ΔT_j (˚C)	T_{jm} (˚C)
1	10	29	140	24	70	80
2	10	26	118	30	60	80
3	10	19	120	46	40	80

f_{SW}: switching frequency, I_{peak}: peak current,
V_{ref}: output reference voltage, T_H: heat-sink temperature,

By this power cycler, power cycling tests can be performed under more realistic electrical conditions close to power electronic applications and mission profile based power cycling test may also be possible.

Fig. 3 shows a prototype of the advanced power cycler.

More detailed information on the power cycler including real-time V_{CE_ON} measurement circuit can be obtained from [11]-[13].

2.2. Test conditions

Power cycling tests are performed under the three operating conditions listed in Table I, which have the same mean junction temperature (T_{jm}) as about 80 ˚C but they have different junction temperature swings (ΔT_j), which are 40 ˚C, 60 ˚C, and 70 ˚C, respectively. The junction temperature swing duration is fixed to 1 s under all test conditions and totally 18 IGBT modules, 6 samples per test condition, are tested. The different temperature swings with the same T_{jm} can be achieved by changing the output current, output voltage and heat-sink temperatures. It is worth to note that in this paper, the junction temperature means the average junction temperature of the whole chip area.

The above test conditions have been set by measuring the junction temperature of an open IGBT module painted with black paint using a high resolution Infra-Red camera.

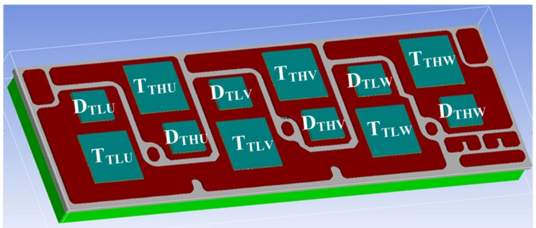

Fig. 4. Internal configuration of IGBT Module under test with 6 IGBTs (T) and 6 diodes (D).

Then, the same electrical and heat-sink temperature conditions have been applied to pristine IGBT modules for the power cycling tests. All test conditions are inside Safe Operating Area (SOA) of the tested device in order to avoid other effects that could come from the operation outside of its SOA.

2.3. IGBT module under test

Fig. 4 shows the internal configuration of the IGBT module under test. It consists of 6 IGBTs and 6 diodes and they are mounted on a Direct Bonded Copper substrate. Aluminum bond-wires are used for the internal interconnection. This module is covered by Epoxy Molding Compound and does not comprise a base-plate. In real applications, the IGBT module under test is operated as inverter mode. Thus, the IGBTs are experienced higher temperature stress than the diodes because losses in the IGBTs are dominant. Therefore, the power cycling tests are focused on the IGBTs.

2.4. Power cycling test results

Typically, 5 % to 20 % increase of V_{CE_ON} is considered as an end-of-life criterion of IGBT modules [1] and the numbers of cycles until these periods are counted for a lifetime. In this paper, 5 % increase of V_{CE_ON} is considered as its end-of-life criterion of individual IGBT module. Further, the power cycling test is stopped if V_{CE_ON} increases by 5 % to 10 % from its initial value to protect the tested IGBT modules against catastrophic failure. In this way, the failure mechanism of tested IGBT modules can be investigated.

Fig. 5 shows the power cycling test result of 5th IGBT module under the condition 1. In this case, the failure occurs in T_{TLV} at around 421000 cycles and it can be also expected that T_{TLU} and T_{TLW} will fail soon. Fig. 6 shows the power cycling test result of 3rd IGBT module under the condition 2. There is no visible increase in V_{CE_ON} of the upper side IGBTs,

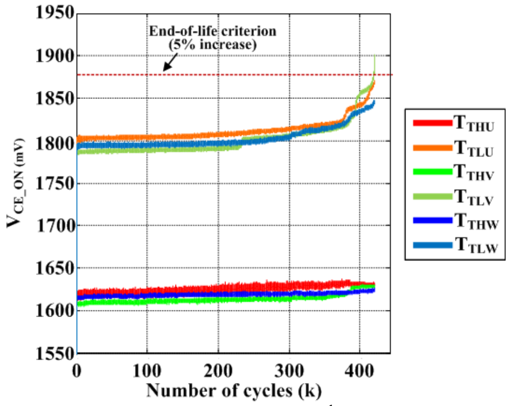

Fig. 5. Power cycling test result of 5th IGBT module under the condition 1.

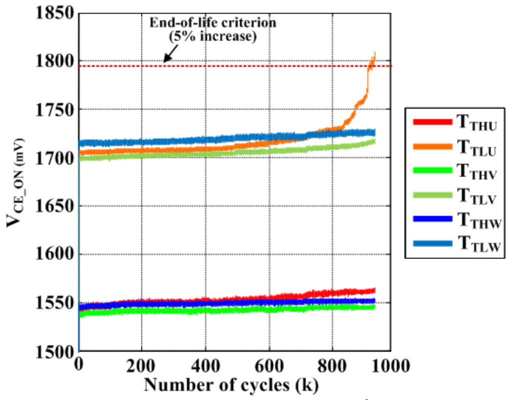

Fig. 6. Power cycling test result of 3rd IGBT module under the condition 2.

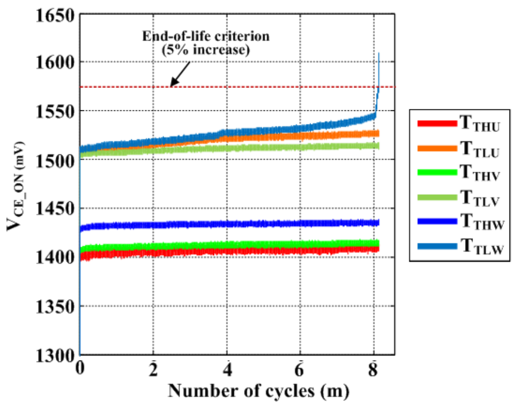

Fig. 7. Power cycling test result of 1st IGBT module under the condition 3.

but V_{CE_ON} of T_{TLU} is reached to the end-of-life criterion at about 933687 cycles. The number of cycles to failure is more than double than that of test condition 1, where there is a difference of 10 ˚C in ΔT_j between condition 1 and condition 2. The power cycling test result of 1st IGBT module under the test condition 3 is shown in Fig. 7.

Table II. Power cycling test results

Cond.	Module	Number of cycles to failure	Failure
1	1	344035	T_{TLW}
	2	387873	T_{TLU}
	3	303527	T_{TLW}
	4	385397	T_{TLV}
	5	420818	T_{TLV}
	6	303327	T_{TLU}
2	1	718360	T_{TLW}
	2	873544	T_{TLW}
	3	933687	T_{TLU}
	4	644695	T_{TLU}
	5	761436	T_{TLU}
	6	493120	Stopped due to external reason. No sign of failure.
3	1	8142724	T_{TLW}
	2	7024197	T_{TLU}
	3	8112082	T_{TLU}
	4	10436704	T_{TLW}
	5	1510357	Stopped due to external reason. No sign of failure.
	6	5143310	T_{TLU}

The failure happens first in T_{TLW} at about 8142724 cycles, which is more than 19 times longer in comparison with the lifetime under condition 1.

The above results show that the temperature swing has a significant effect on the lifetime of the target IGBT module in this paper. Moreover, the low side IGBTs are obviously weaker than the upper ones. The reason why the failure at low side IGBTs occurs earlier has been explained in [11].

All power cycling test results under the three different junction temperature swings are summarized in Table II. The power cycling tests for 6th IGBT module under the condition 2 and 5th IGBT module under the condition 3 have been stopped at 493120 and 1510357, respectively because the electric fuse has been activated during power cycling test due to over current caused by an external reason. This is not due to the IGBT module failure. However, the power cycling tests for these modules were not performed again.

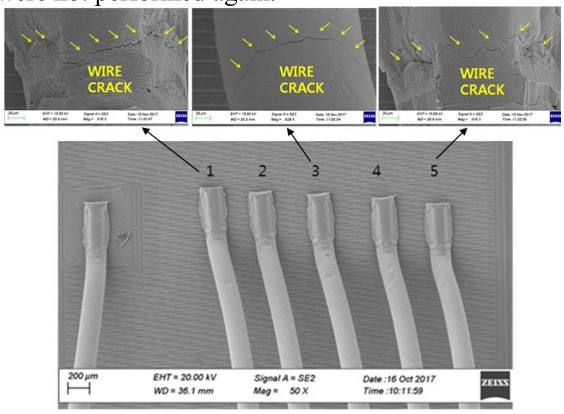

Fig. 8. SEM image of 1st tested IGBT module under the condition 3.

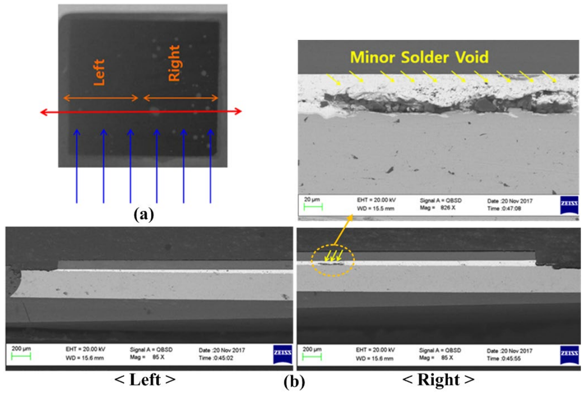

Fig. 9. SEM images of 1st tested IGBT module under the condition 3 (a) vertical polishing location and direction (b) cross sectioned view.

3. Failure Analysis of IGBT Modules

Fig. 8 shows a Scanning Electron Microscopy (SEM) image of 1st tested IGBT module under the condition 3. Cracks are observed in bond-wires of T_{TWL} which is the first failed device among 6 IGBTs (See Fig. 7). The cracks in bond-wires are also observed in the other tested modules under the same condition. Furthermore, the same failure mechanism is seen in the tested IGBT modules under the other conditions.

Fig. 9 shows the cross-section SEM images of the same IGBT module shown in Fig. 8. There is no visible degradation in the solder-joint. A minor solder void is observed but it is not due to the power cycling test but from initial manufacturing process. No bond-wire lift-off and solder-joint fatigue have been observed in any tested IGBT modules.

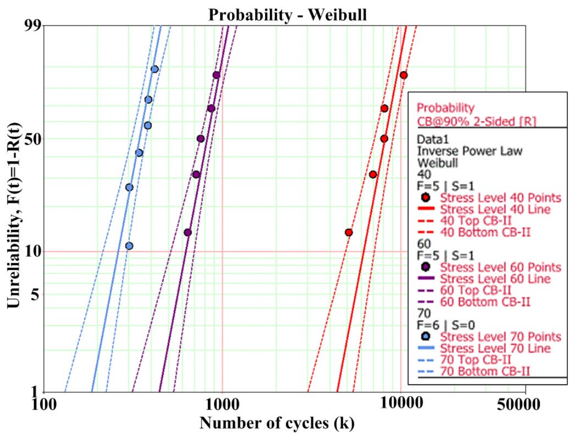

Fig. 10. Weibull plot of power cycling test results.

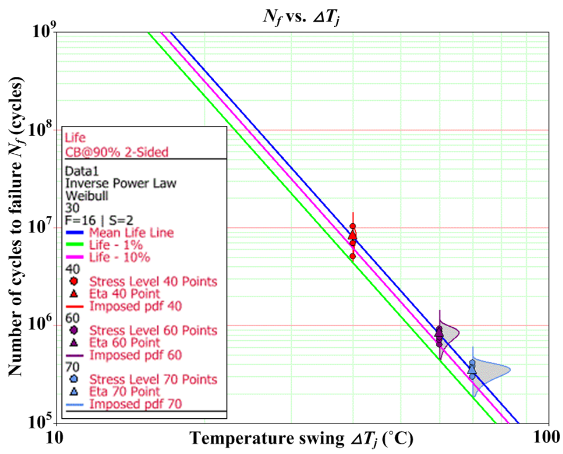

Fig. 11. Number of cycles to failure as a function of junction temperature swing.

According to the failure analysis results, the bond-wire crack is the predominant failure mechanism of the tested IGBT modules under the test conditions defined in Table I. There is no significant difference in the dominant failure mechanism among 18 IGBT modules due to the different temperature swings in the defined ranges.

It is worth to note that the tested IGBT module does not have base-plate. Therefore, the observed dominant failure mechanism could be different in the case of the different packaging technologies.

4. Junction Temperature Swing Dependent Lifetime Analysis based on Test Data

The number of cycles to failure (N_f) of the tested IGBT module under three test conditions, shown in Table II are presented by Weibull distribution and analyzed by using the software tool Weibull++ [12].

Table III. Parameters of model (1) for the selected lifetime definitions

Lifetime	A	n
B_1	5.03856E+15	-5.6545
B_{10}	7.09526E+15	-5.6545
MTTF	9.20325E+15	-5.6545

The lifetime of a population of IGBT modules can be defined with different criteria in terms of time to how much percentage of accumulated failure. For example B_1 lifetime, it is the time to 1 % of total population is fail. B_{10} lifetime is the time to 10 % of total population is fail. Further, it is important to obtain the predicted lifetime range with a certain Confidence Boundaries (CB) because the time to failure of each IGBT module varies.

Fig. 10 shows the Weibull plots under the three test conditions with 90 % CB. From Weibull plots, the selected lifetime curves, which are B_1, B_{10} and *MTTF* (mean time to failure) lifetimes based on inverse power law with probability distribution function (pdf) at each stress level are obtained as shown in Fig. 11, where β is 6.864.

The effect of junction temperature swing on the lifetime of IGBT modules can be modeled by inverse power law as

$$N_f = A \cdot (\Delta T_j)^{-n} \qquad (1)$$

where N_f = the number of cycles to failure, ΔT_j = temperature swing, and A and n are fitting parameters based on power cycling test results.

Table III shows the parameter values of the lifetime model (1) for the selected lifetime definitions. From this lifetime model, the lifetime of IGBT module at the given junction temperature swing can be estimated.

5. Conclusion

In this paper, the effect of junction temperature swing on lifetime and failure mechanism of 600V, 30A, transfer molded IGBT modules has been investigated by an advanced power cycler. It can be clearly seen from the results that ΔT_j has a significant effect on the lifetime of the target IGBT module.

Furthermore, a post-failure analysis has been performed to investigate the main failure mechanism of the tested IGBT module. Bond-wire cracks are observed in all tested IGBT modules and there are no visible degradations in the chip solder-joint and at the interface between bond-wires and chips, which is preliminary phenomenon of bond-wire lift-off. Therefore, bond-wire crack is the predominant failure mechanism of the target IGBT module under the considered stress range.

Finally, the junction temperature swing dependent lifetime factor has been extracted based on a total of the 18 power cycling test results under three different junction temperature swings. The different lifetimes are obtained with different lifetime definitions and confidence levels of a specific lifetime. The result shows the importance of the information about the lifetime definition and the confidence level for the lifetime modeling. This study enables to estimate the lifetime of the target IGBT module when the junction temperature swing is given. However, more power cycling test results under various test conditions such as different mean junction temperatures and different junction temperature swing durations are needed in order to develop more complete lifetime model including the effects of junction temperature swing, mean junction temperature and junction temperature swing duration on the lifetime of the IGBT module.

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