First results of development of a lifetime model for transfer molded discrete power devices

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Abstract

The research on lifetime models of power module has already started in the late 1990s. However for the transfer molded discrete package, there is still a shortage of investigation on their power cycling capability regarding lifetime impacting parameters. In this work, first results of developing a lifetime model for transfer molded discrete power devices are shown. Through a study with original devices and locally opened devices of the same type, the impact of epoxy resin molding compound on power cycling capability was investigated.

1. Introduction

The power cycling test is an important reliability and quality assessment method, which is often used for the development of lifetime model for power semiconductor devices. Since the LESIT project [1], the study on lifetime models of power module has never stopped. The parameters, which could influence the power cycling lifetime of power modules have been investigated in detail with a plenty of power cycling tests [2], [3]. However for transfer molded discrete power devices, the research works are much less. Although in some former publications [4], [5], [6], transfer molded discrete power devices were proven to have a high power cycling capability. In power cycling tests with transistor outline (TO) packages, TO-247 package (see [4]) and TO-263 package (see [6]) were proven to have even higher power cycling capability compared to standard power modules in that time.

Based on the publication results, more than 60% of the power cycling tests of power modules from 1994 until now were performed on Insulated Gate Bipolar Transistors (IGBTs) [7]. In this work, several power cycling tests were performed on IGBTs of eight different devices (voltage and current class) in the TO-247 package from Infineon. The first results of development of a lifetime model for this package are shown in this paper.

2. Design of experiments

2.1. Impact of design parameters

In the CIPS 08 model [2], design parameters like chip thickness, bond wire diameter and current per bond foot were identified to have an impact on the power cycling capability of power modules. In the first test series of this work, eight different devices were tested under the same test condition (gate voltage V_{GE} = 15 V, junction temperature swing ΔT_j ≈ 90 K, mean junction temperature T_{jm} ≈ 105°C, load pulse duration t_{on} = 2 s, and t_{off} = 4 s). A high ΔT_j ≈ 90 K was selected to accelerate the test. The test conditions of the first test series is summarized in Table 1. I_{bf} is the current per bond foot and I_b is the current per bond. The target of this test series is to investigate the impact of design parameters.

Table 1. Test conditions of the first test series

DUT	V_{CES} in V	I_b in A	I_{bf} in A	P_V/A_A in W/mm²	ΔT_{md} in K (FEM)
1	1200	15.4	7.7	2.2	2.4
2	1200	19.4	19.4	4.3	4.7
3	600	24.4	24.4	7.9	9.5
4	650	30.4	30.4	5.5	6.2
5	1200	15.5	15.5	7.0	7.0
6	1200	17.6	8.8	3.5	3.8
7	600	26.9	26.9	6.0	6.8
8	600	30.9	30.9	14.2	13.6

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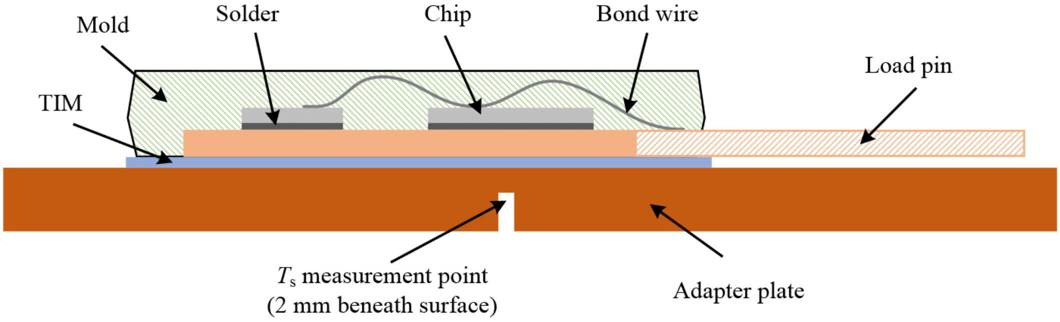
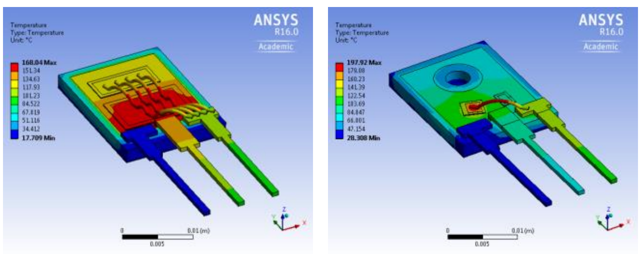


Fig. 1. Schematic cross section of TO-247 device and definition of heat sink temperature T_s

The selection of devices was done in a way to cover a broad variation in parameters that could have an impact on power cycling performance. In this work, voltage class of the devices varies from 600 V to 1200 V (varying chip thickness) and current class of the devices varies from 20 A to 75 A. Device 1 and 6 are the only two device types with double-stitch bonding, whose bond wires have two bond feet per bond wire on IGBT chips.

A schematic cross section image of the device under test (DUT) is shown in Fig. 1. The device is fixed through spring clip or screw on a copper adapter plate. The heat sink temperature T_s was measured 2 mm beneath the surface of the Cu adapter plate by thermocouples. In the TO-247 package from this work, semiconductor chips are soldered on a 2 mm copper base, which is directly connected to the collector load pin. The surface of the IGBT and diode chip is connected to the emitter load pin by aluminum bond wires.



(a) (b)

Fig. 2. FEM model of DUT 1 (a) and DUT 8 (b)

During power cycling tests, a measurement delay t_{md} = 500 µs is used for the measurement of maximal junction temperature T_{jmax}. Details on method and accuracy of measurement are given in [8]. It is found by using finite element method (FEM) simulation that devices in this work will cool down for about 1.1 K in 500 µs at a power loss per active area P_V/A_A = 1 W/mm^2 (see Table 1). As can be seen clearly from Fig. 3, device DUT 1 and DUT 8 with extreme different power loss density have an enormous difference in the measurement errors caused by t_{md}. Therefore, measurement results of T_{jmax} from power cycling tests were first corrected with FEM simulation results.

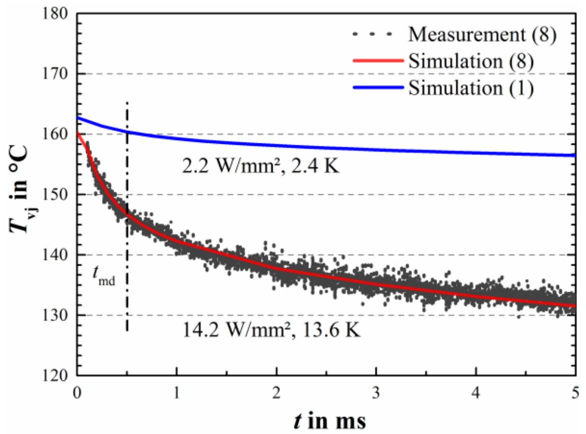


Fig. 3. Measurement and FEM simulations results of the first 5 ms after turn-off of DUT 1 and DUT 8

2.2. Impact of mold compound

It was found in [9], [10], that polymer (PI) coating can suppress bond wire lift-off and the aluminum metallization reconstruction effect. Therefore, PI coating is sometimes used to protect bond wires in power modules. Similar like PI, mold compound is also a hard material, which could suppress the deformation of bond wires during power cycling test and hold the bond feet from lift-off. The authors believe that transfer molded discrete packages have a high power cycling capability regarding bond wire failure due to the effect of the epoxy resin molding compound.

In this work, to further investigate the impact of mold compound on power cycling lifetime, a case study was done with original devices and locally opened devices from device type 8. As shown in Fig. 4, on the top of the target IGBT chip, mold compound was removed by using laser and acid.

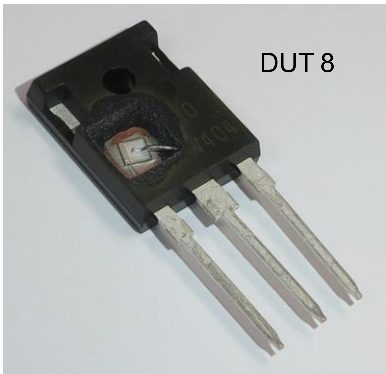


Fig. 4. Locally opened device for comparative study

2.3. Lifetime modelling

The main target of this work is the development of a lifetime model for transfer molded discrete power devices. Similar like the CIPS 08 model shown in Eq. 1 [2], impact of parameters like ΔT_j, T_{jm}, I_L, and t_{on} on power cycling lifetime is to be studied.

$$N_f = K \cdot \Delta T_j^{\beta_1} \cdot e^{\frac{\beta_2}{T_{jmin}+273}} \cdot t_{on}^{\beta_3} \cdot I^{\beta_4} \cdot V^{\beta_5} \cdot D^{\beta_6} \quad (1)$$

Device type 8 was chosen for the investigation of lifetime model, since it is the simplest device with only one bond wire and one bond foot for load current (see Fig. 4). A series of power cycling tests with different test conditions were performed on this device type. A summary of the finished tests up to now is given in Table 2. For all these seven tests, V_{GE} = 15 V and t_{on} = 2 s were used. From the finished tests, dependency of lifetime on ΔT_j (Coffin-Manson) and T_{jm} (Arrhenius) can be already determined.

Table 2. Test conditions of the second test series

Test	ΔT_j in K	T_{jm} in °C	I_L in A	ΔT_{md} in K (FEM)
1	50	125	21.5	7.5
2	70	85	27.5	10.6
3	70	95	27.5	11.0
4	70	105	27.0	11.0
5	70	125	26.5	10.8
6	90	85	31.9	14.2
7	90	105	30.9	13.4

3. Test results

3.1. Impact of design parameters

As already shown in Table 1, different devices have different systematic measurement offsets ΔT_{md} due to the measurement delay. Therefore, for a fair comparison, measurement results of ΔT_j and T_{jm} of all devices should be first corrected with results of FEM simulation. Then the power cycling lifetime of each device is normalized to the same test condition (ΔT_j = 90 K and T_{jm} = 105°C) by using Coffin-Manson exponent α = -3.56 and activation energy E_A = 0.168 eV based on Eq. 2 (see more details in part 3.3).

The normalized lifetime of all devices are plotted over load current per bond foot I_{bf} in Fig. 5 and over load current per bond I_b in Fig. 6. Device type 1, 2, 5 and 6 with squares are 1200 V device and device type 3, 4, 7 and 8 with circles are 600 V or 650 V devices. At first glance, it seems like 1200 V devices have in general higher power cycling capability than 600 V or 650 V devices under the same test conditions. It is however to be noted, that 1200 V devices usually have higher forward voltage drops than 600 V devices at the same

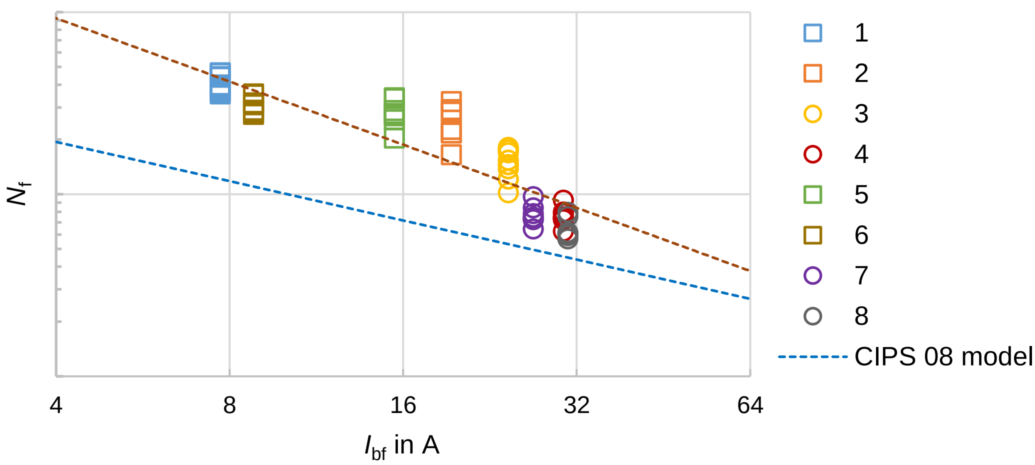


Fig. 5. Normalized lifetime plotted over load current per bond foot (ΔT_j = 90 K, T_{jm} = 105°C)

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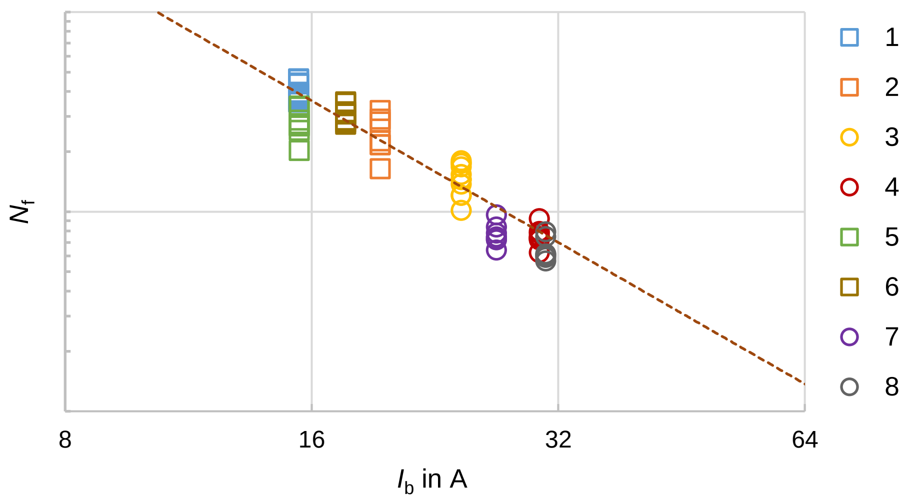

Fig. 6. Normalized lifetime plotted over load current per bond (ΔT_j = 90 K, T_{jm} = 105°C)

current, since 1200 V chips are thicker. Therefore for the same rated current, chips of 1200 V devices should be larger than chips of 600 V devices in order to have the same specified maximum operating junction temperature (usually 175°C). In this case, more bond wires could be fixed on the 1200 V chips, since the chips are larger. As a result, I_b of 1200 V devices is always lower than I_b of 600 V devices under the same test condition. Due to above mentioned reasons, voltage class (chip thickness) and current per bond are related to each other and could not be varied individually. It can however be seen from Fig. 6 that within the same voltage class group, power cycling lifetime of the devices still strongly depends on the load current. The test results of different voltage classes meet well with the same fitting based on the power law. Therefore, no dependency of power cycling lifetime on chip thickness can be confirmed in this test series for bond wire failure (t_{on} = 2 s). For longer heating time, chip solder may become the weak part in power cycling test and chip thickness might have an impact.

It is clear to see from Fig. 5 and Fig. 6, transfer molded power devices have a strong dependency of power cycling lifetime on load current per bond wire. The main reason is the self-heating effect of the aluminum bond wire by its own conduction losses. As the Fig. 6 shows, I_b of devices tested in this work is in the range of 15 A to 30 A, which is much higher than the typical value in tests of power modules (usually smaller than 10 A, see [2]). Therefore, a much stronger self-heating effect of bond wire in discrete devices under power cycling tests is to be expected. According to the FEM simulation, temperature difference between chip surface and bond heel point depends strongly on the load current per bond. In some cases with extreme high I_b, this temperature difference could be even greater than 20 K. Therefore, the chip temperature measured via pn-junction forward voltage will not completely represent the stress condition of bond wires in discrete devices under accelerated power cycling tests. Besides, once the bond wire starts to degrade (inception of the first crack), the electrical resistivity of the failure position will increase. With higher current, more heat will be then generated locally at the failure position. Thus, the degradation of this failure position will be accelerated stronger at a higher current.

In all devices, no significant increase in thermal resistance R_{thjs} was found. As can been confirmed by scanning acoustic microscopy (SAM) images (see Fig. 7), no degradation of the chip solder is visible after test. Compared to the untested diode chip shown in Fig. 8, clear degradation of the interface between bond wire and IGBT chip can be seen after test.

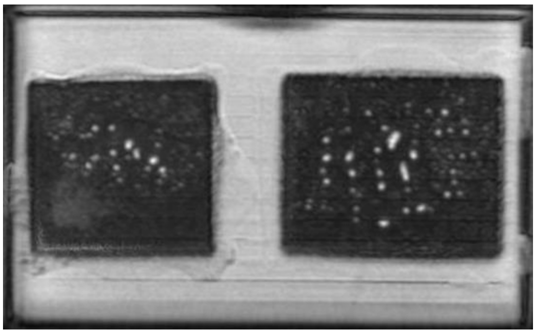

Fig. 7. SAM image of chip solder after test (DUT 4)

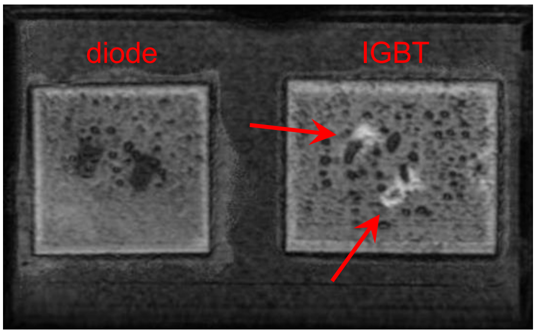

Fig. 8. SAM image of chip surface after test (DUT 4)

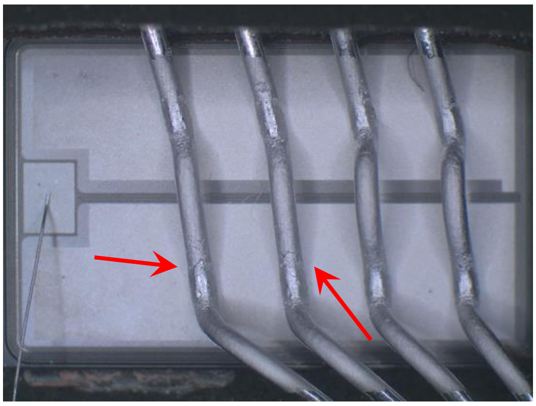
Fig. 9. Heel crack in bond wires after test (DUT 1)

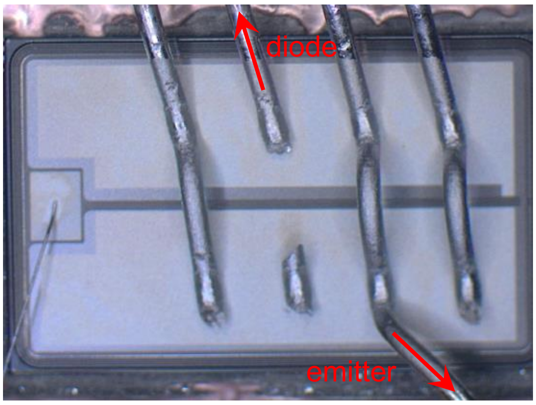

Fig. 10. Heel crack in bond wires after test (DUT 1)

For all devices, the failure criteria in the test has been defined as an increase of forward voltage at load current by 5%. The main failure mechanism is heel crack in bond wire (see Fig. 9, 10 and 12). Cracks in bond wire as predominant failure mechanism were also found in similar transfer molded IPMs (intelligent power modules) [11]. In some devices of this work, bond wire lift-off can also be found after the test (see Fig. 11). For devices with double stitch bonding (see Fig. 10), most heel cracks were found near the first row of bond feet, where the total load current flows to the emitter load pin. It is to be expected that the bond heels in this row have higher temperature during the tests due to stronger self-heating effect. Therefore the fitting results shown in Fig. 6 (current per bond) are better than the fitting results shown in Fig. 5 (current per bond foot).

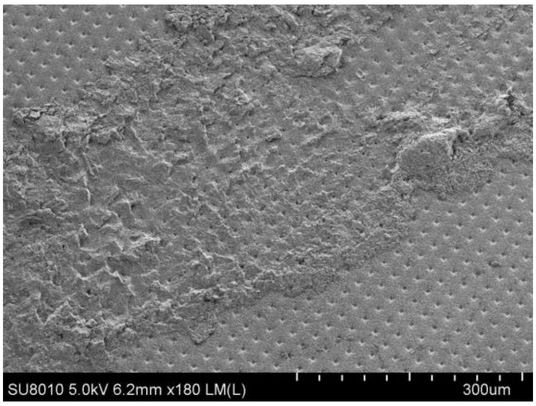

Fig. 11. SEM image of footprint from a detached bond wire (DUT 2)

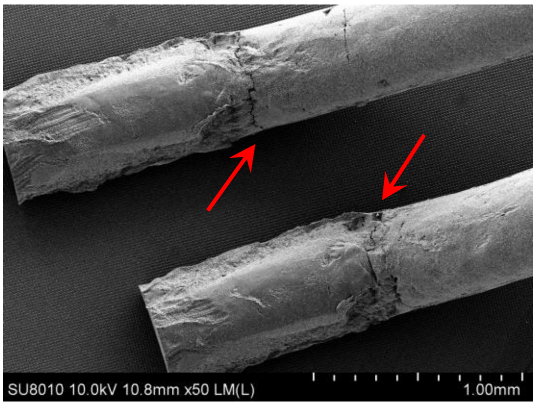

Fig. 12. SEM image of heel crack in bond wire (DUT 3)

As Fig. 5 shows, transfer molded discrete power devices show in general higher power cycling capability than standard power modules from CIPS 08 model [2]. The main reason is that mold compound can suppress bond wire lift-off and the aluminum reconstruction effect (details see part 3.2.). It is to be noted that in former lifetime models for power modules, the measurement error caused by the measurement delay was usually not corrected. However since the power loss density of power module under power cycling tests is much lower than for discrete devices, the measurement error is also much smaller (usually < 3 K).

3.2. Impact of mold compound

In order to find out the impact of mold compound on power cycling capability, original devices and locally opened devices of the same type were tested under three different test conditions. As for

example shown in Fig. 13, original device #133 has achieved about three times higher power cycling lifetime than the locally opened device #11. The test conditions of both devices are almost the same. A summary of the test results is given in Fig. 14. For all three test conditions, locally opened devices have achieved much less test cycles than the original devices.

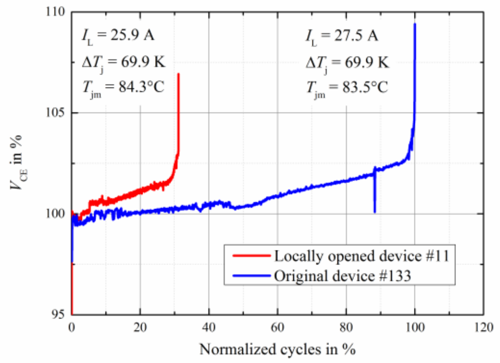

Fig. 13. Raw test results of device #11 and #133

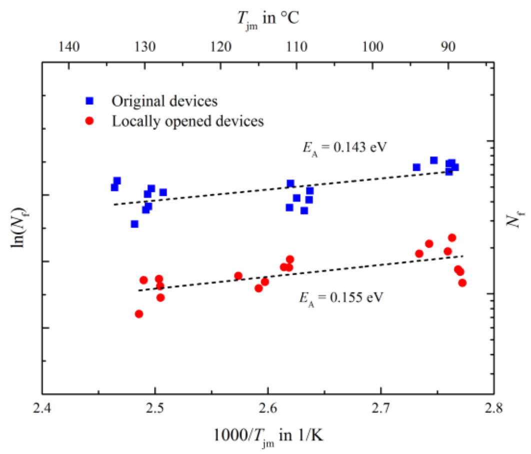

Fig. 14. Normalized lifetime plotted over T_{jm} (I_b = 20 A and ΔT_j = 70 K)

Fig. 15. Cross sectional cut of a bond wire with crack after power cycling test (locally opened device #1)

Due to the removal of mold compound, no extra protection is given to the bond feet. As can be seen from Fig. 15, a clear crack through the lower part of the bond wire is found after test. This failure mechanism is similar to the bond wire failure of power modules with silicone gel shown in [12]. Another small crack in the bond heel part is also visible, which is however not large enough for the failure. The main failure mechanism of the locally opened device under the given test conditions is bond wire lift-off.

3.3. Lifetime model

Up to now, seven different tests were performed on device type 8. For each test, at least six devices were tested till end of life. All devices from this test series have achieved their failure limit with an increase of V_{CE} by 5%. The corresponding main failure mechanism is bond failure.

The lifetime model (see Eq. 2) was calculated by least square fit on the complete results with the basis lifetime K, the Coffin-Manson exponent α, junction temperature swing ΔT_j, the activation energy E_A, Boltzmann constant k_B, mean junction temperature T_{jm} in Kelvin and power factor γ for current per bond I_b.

$$N_f = K \cdot \Delta T_j^{\alpha} \cdot e^{\frac{E_A}{k_B \cdot T_{jm}}} \cdot I_b^{\gamma} \qquad (2)$$

Since the mean junction temperature T_{jm} can be varied individually though different coolant inlet temperature T_{inlet}, results of the investigation of the Arrhenius term are first analyzed and summarized in Fig. 16. For results with different temperature swings, a reduced lifetime with increased mean junction temperature can be confirmed. Based on the test results up to now, an activation energy E_A = 0.168 eV is derived for the devices in this work with bond wire failure. A summary of E_A of bond wire failure from other research groups is given in Table 3.

Table 3. Summary of E_A of bond wire failure

Source	E_A in eV	Comments
This work	0.168	Al bond in TO-247 package
LESIT [1]	0.808	Al bond in traction module
CIPS 08 [2]	0.111	Al bond and solder failure
Schilling [12]	0.080	Al bond in high power module
Schmidt [13]	0.069	Al bond in power module
Scheuermann [3]	0.066	Al bond in power module

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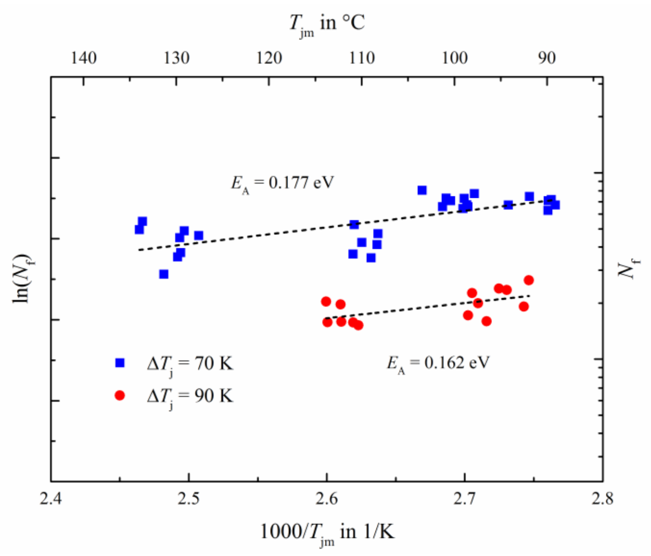

Fig. 16. Normalized lifetime plotted over T_{jm} (I_b = 20 A)

Since the dependency of lifetime on load current was already found in the first test series, the fitting results for γ from Fig. 6 was directly used for the normalizing of test results of different temperature swings. The normalized lifetime of all devices are then plotted over corrected temperature swing ΔT_j in Fig. 17. For bond wire failure, a Coffin-Manson exponent α = -3.56 is found. This value is similar like the value written in the quality information from Vishay Semiconductors (α = -3.5 for Al wire bond failure, see [14]). For power modules, the Coffin-Manson exponent α is typically in the range of -4 to -5 (see [1], [2], [3]).

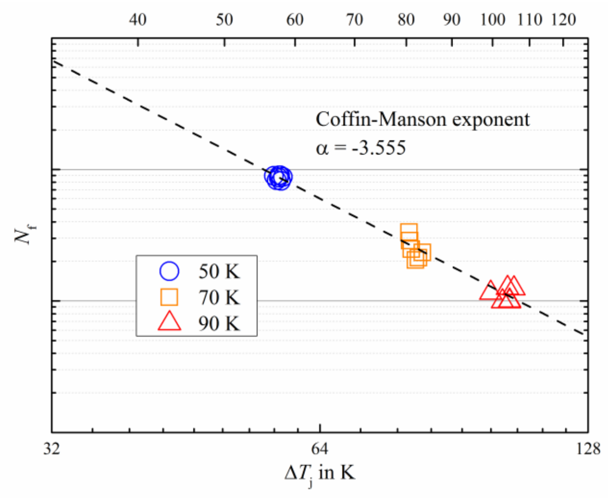

Fig. 17. Normalized lifetime plotted over corrected ΔT_j (I_b = 20 A and T_{jm} = 105°C)

In order to verify the accuracy of the lifetime model, the expected lifetime based on the lifetime model was then calculated for all tested devices in this work. A comparison of the expected lifetime with original test results is shown in Fig. 18. It is clear to see that the expected lifetime fits well with the test results. It is to be noted that lifetime model shown in this work is given for the purpose of scientific research without considering any safety margin.

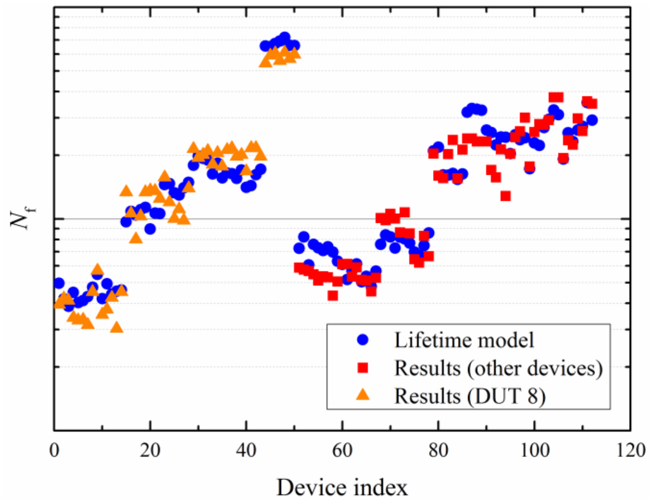

Fig. 18. Power cycling results compared to the results calculated with proposed lifetime model

4. Conclusions

In this work, two series of power cycling tests were performed on eight different device types in the TO-247 package and more than 110 devices were tested till end of life. All devices have failed during the power cycling tests with bond wire failure.

In the first test series, load current was found to have a great impact on the power cycling capability of TO-247 package. Heel crack is the predominant failure mechanism for the devices tested in this test series with a load pulse duration t_{on} = 2 s. For the bond wire failure, no dependency of lifetime on chip thickness is expected and it is also indirectly confirmed by the results from this work. In general, as a representative of transfer molded discrete power devices, the TO-247 package has shown a high power cycling capability and it is competitive for application in the industrial regime.

Through a comparative study with original devices and locally opened devices, the impact of mold compound on the power cycling lifetime was investigated. It was found that mold compound as a protection material for the bond wire could suppress the bond wire lift-off effect and extent the power cycling lifetime of the devices. Devices without mold compound have failed with bond wire lift-off like standard power modules (with silicone

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gel) without polymer coating.
In the second test series, the dependency of lifetime on junction temperature swing ΔT_j and mean junction temperature T_{jm} was investigated. The parameters of the lifetime model were calculated for the TO-247 package with a least square fit. The value of the Coffin-Manson exponent α is in a comparative range of the values from other publications. For the activation energy E_A, the value is higher than the dependency quoted for power modules from recent publications

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