

# Power Cycling with High Temperature Swing of Discrete Components based on Different Technologies

R. Amro, J. Lutz

TU Chemnitz, Reichenhainerstr. 70, A.-F.-Weinhold-Bau, Raum H123, D-09126 Chemnitz

A. Lindemann

IXYS Semiconductor GmbH, Edisonstr. 15, D-68623 Lampertheim

**Abstract-** We present the results of power cycling tests of transfer molded, DCB and copper based power components at temperature swings up to 155K. The results of the DCB based components are statistically analysed with Weibull distribution. An Analysis of the components after the tests provide an overview on the failure mechanisms. The results of the DCB based, transfer molded components exceed the expectations based on extrapolation of LESIT results.

## I. INTRODUCTION

The environmental conditions of power modules, especially with respect to the maximum specified temperature are getting harsher. In automotive applications e.g. some parts of the electronic will move under the hood [1], where the modules are subjected to an environmental temperature higher than 100 °C. Therefore, automotive standard AEC-Q101 stipulates that power components must withstand 5000 power cycles at temperature swings higher than 100K. To fulfil the requirements in reliability and costs the demand for module lifetime prediction of given packaging concepts at high temperature increases.

During LESIT project standard modules with base plate have been tested. At the end of the project a considerable data-base was collected [2]. The results for different temperature swings at three medium temperatures are shown in Fig.1.

All three lines of the fit in fig.1 can be expressed by the equation [3]:

$$N_f = A \cdot \Delta T_j^\alpha \cdot \exp\left(\frac{E_a}{k_B \cdot T_m}\right) \quad (1)$$

with

$N_f$  = number of power cycles

$k_B$  = Boltzmann-constant =  $1,380 \cdot 10^{-23} \text{ JK}^{-1}$

$E_a$  = activation energy =  $9,89 \cdot 10^{-20} \text{ J}$

$A$  = constant =  $302500 \text{ K}^{-\alpha}$

$\alpha$  = constant =  $-5,039$

$T_m$  = medium junction temperature [K]

However, since the completion of LESIT project, many packaging concepts have been developed; in addition it is not clear whether the equation derived by LESIT-project can be extrapolated towards higher temperatures.

## II. PACKAGING TECHNOLOGIES

In the transfer molded, DCB based technology the power semiconductor chips are soldered onto a DCB ceramic substrate together with a lead frame with up to five pins. Subsequently chips and DCB are covered by molding compound. This packaging method combines the technologies of module and discrete assembly. Thus the resulting component provides a combination of the characteristics of both families of devices [4]. Figure 2 shows the cross section of a DCB based transfer molded package.

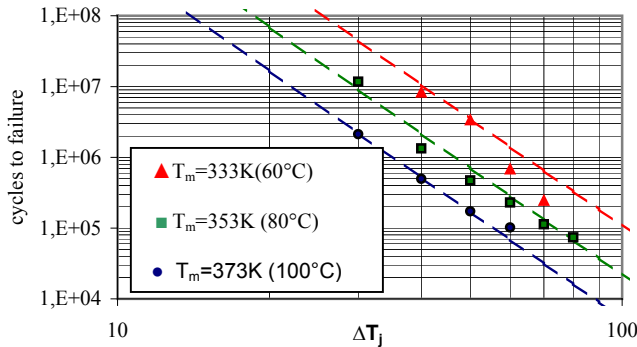


Fig.1: LESIT results for different  $\Delta T_j$  [2]

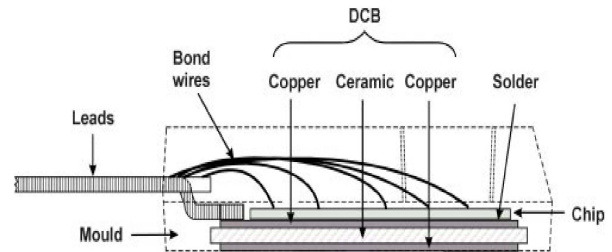


Fig.2: cross section of transfer molded DCB based component

DCB (Direct Copper Bonding) denotes a process in which two copper layers are bonded onto the top and the bottom

of a ceramic substrate. The bottom copper is used to transfer the operational heat dissipation while the top copper carries the chips, whose upper side is wire bonded towards the DCB pattern and the pins. DCB substrates are produced in form of cards which are cut to the requested substrate size.

In the transfer molded copper based technology the top side of the power semiconductor chip is wire bonded while the bottom side is soldered on copper lead frame. The package is typically moulded plastic to fix the leads for external electric connections. This technology provides low processing costs, however the required external isolation between circuit and heat sink increases mounting effort. Furthermore, reliability is restricted by mismatch of thermal expansions coefficients of silicon chip and copper lead frame[5]. Figure 3 shows a cross section of copper based transfer molded component.

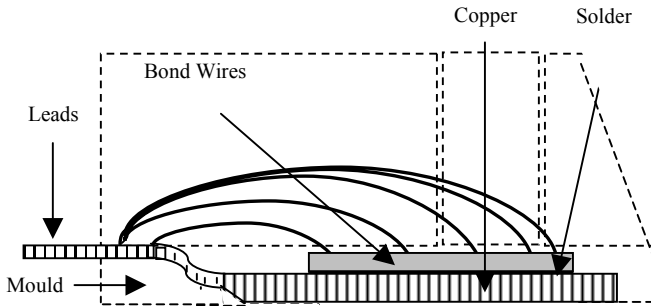


Fig.3: cross section of transfer molded copper based component

### III. POWER CYCLING TEST CIRCUIT

Six series connected diodes are mounted on three Al heat sinks and were simultaneously heated by applying half-sinusoidal load current. After reaching the defined upper temperature, load current is turned off and forced air cooling is turned on. Failure criteria, which decide that a diode has reached its end-of-life are:

- An increase of the forward voltage  $V_F$  at 50A and room temperature of 20% with respect to the initial value.
- An increase the thermal resistance between junction and heat sink ( $R_{thj-h}$ ) of 20% with respect to the initial value, or
- Leakage current  $I_R$  exceeds 1mA.

The three failure indicators were measured or calculated at regular basis and after stopping the runs.

The duration of the heating-up and cooling-down phases was controlled by adjustable maximum and minimum heat sink temperature. The advantage of choosing the heat sink temperature as control parameter is the exclusion of the influence of the cooling mechanism and at the same time the inclusion of effects caused by changes in thermal resistance [3].

The Heat sink temperature was measured by a thermal couple fixed on the centre heat sink, ca. 1mm underneath

the power component (see Figure 4). Experiences have shown that at this distance parasitic effects resulting from heat sink parameters like size, thermal conductivity etc. are minimized [6].

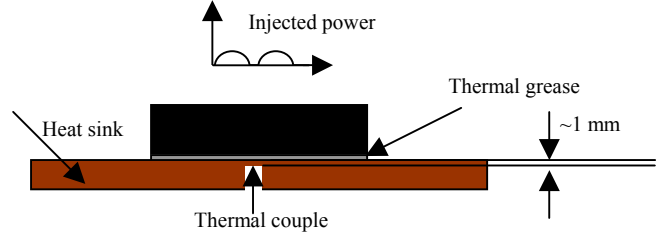


Fig.4: Position of heat sink temperature measurement and control

The load current, generated by a B2 rectifier bridge, exhibits breaks of ca. 2ms. A continuously flowing sense current of 50mA is superimposed to the load current, during the break the forward voltage drop at 50mA can be measured. The forward voltage drop at 50mA is used to determine the junction temperature, a calibration measurement is done before the test.

### IV. TEST RESULTS

#### A. Test results of the DCB based, transfer molded diodes

Three power cycling tests have been carried out. In each test, three identical half bridge components with chip area of  $63 \text{ mm}^2$  per diode have been power cycled. Figure 5 shows the type of the components under test and table 1 summarizes the most important parameters of the tests.

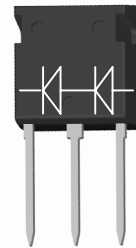


Fig.5: DCB based transfer molded half-bridge (DSEE55 24N1F)

TABLE 1: PARAMETRES OF POWER CYCLING TESTS WITH DCB BASED, TRANSFER MOLDED DEVICES

Test Nr.	$T_{j,min}$ (°C)	$T_{j,max}$ (°C)	$\Delta T_j$ [K]	Heating-up time (ton) [s]	Coolig-down time (toff)[s]	Load current ( $I_{L,ave}$ ) [A]
1 (PC1)	40	145	105	38	56	18
2 (PC2)	40	170	130	20	70	28
3 (PC3)	40	195	155	28	85	32

A representative behaviour of  $T_{j,max}$  and  $V_F$  during PC1 is shown in figure 6. The graphic shows that a small increase of  $T_{j,max}$  can be observed after approximately 30000 cycles, while a significant increase of  $V_F$  can be detected after approximately 60000 cycles. Exceeding of the allowed 20% of the initial value of  $V_F$  was the dominant failure mode in this test.

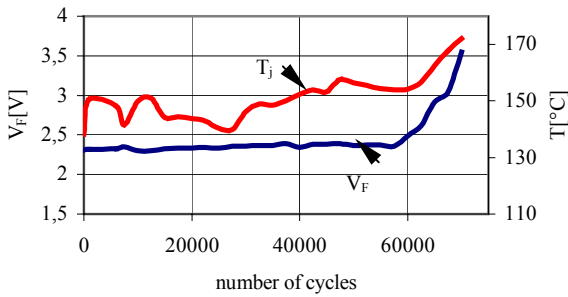


Fig.6: Power cycling test for  $\Delta T_j=105K$

Figure 7 shows a photograph of a component of PC1 taken with the electron microscope after test stop. One can observe the trace of a completely lifted of wire and the heel cracking of the adjacent wires.

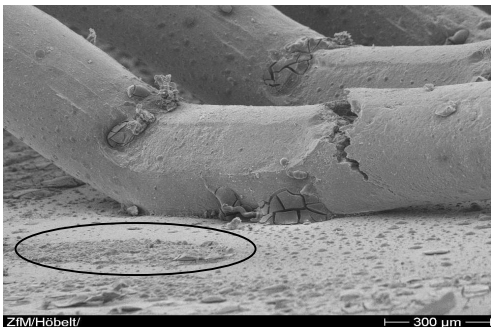


Fig.7: Bond wire lift-off and heel cracking of a diode power cycled at  $\Delta T_j=105 K$

It is noticeable that the above picture is from a diode which didn't fail till test stop at 75000 power cycles, however it is obvious that failure would have occurred soon.

In PC2 ( $\Delta T_j=130K$ ) the majority of the tested diodes shows no significant increase of  $V_F$ , however a clear increase of  $T_j$

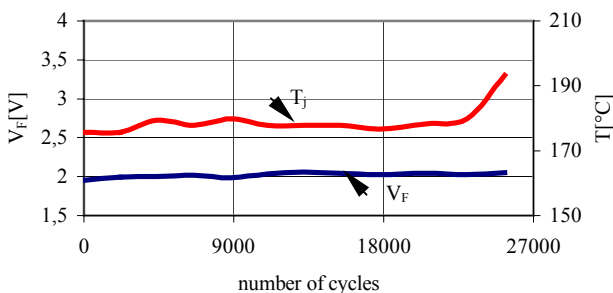


Fig.8: Power cycling test for  $\Delta T_j=130K$

was obvious. A typical behaviour of  $V_F$  and  $T_j$  during this test is shown in Figure 8

Exceeding the maximum allowed increase of the thermal resistance from junction to heat sink ( $R_{th,j-h}$ ) was the dominant failure mode. However, analysis of the diodes after test has shown that bond wires of some diodes have aged too; (figures 9a ,9b). The failure mechanisms of bond wires and the solder fatigue seem to occur at virtually the same time.

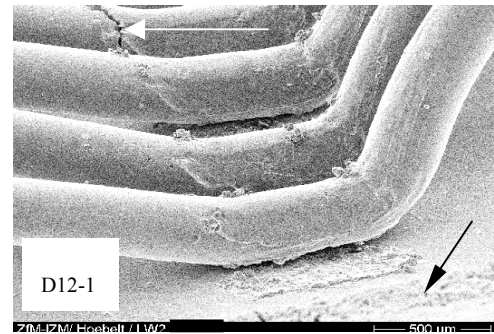


Fig. 9a: Bond wire lift-off and heel cracking of a diode power cycled at  $\Delta T_j=130K$  (wires toward metallization)

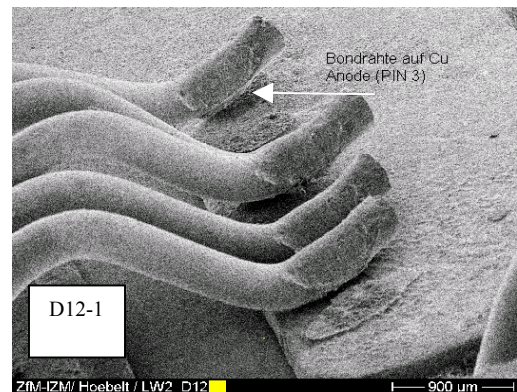


Fig. 9b: Bond wire lift-off and heel cracking of a diode power cycled at  $\Delta T_j=130K$  (wires toward DCB)

Diodes power cycled in PC3 ( $\Delta T_j=155K$ ) showed a similar thermal and electrical behaviour to the diodes in PC2. However, increase of thermal resistance by solder fatigue could be clearly identified as the main failure mechanism in this test. Analysis of the diodes after test support this diagnosis (Figure 10).



Fig.10: Bond wires of a diode power cycled at  $\Delta T_j=155K$ , no aging of bond wires is detectable

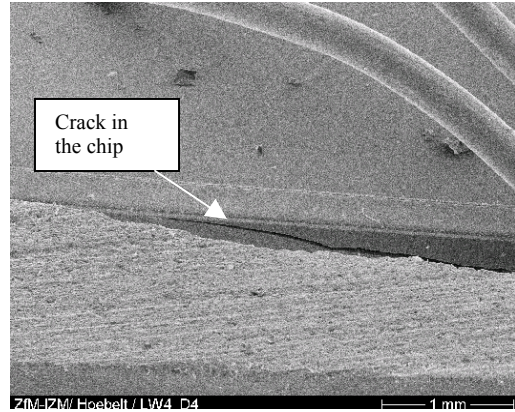


Fig.12: Chip crack of copper based, transfer molded diode power cycled at  $\Delta T_j=110K$

### B. Test results of copper based, transfer molded diodes.

A group of six diodes have been power cycled at  $\Delta T_j=110K$ . Pictures of the tested diodes are shown in figures 11a and 11b. The most important test parameters are listed in table 2

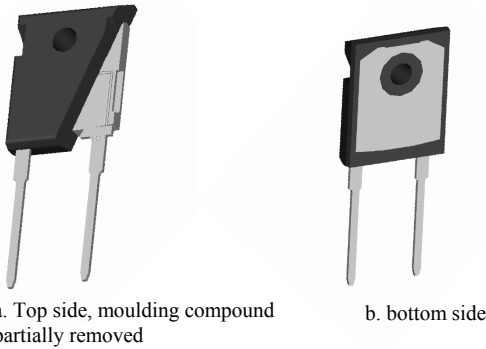


Fig.11: Copper based, transfer molded TO 247

TABLE 2: PARAMETRES OF POWER CYCLING TESTS WITH COPPER BASED, TRASNFER MOLDED DEVICES

Test Nr.	$T_{j,min}[^{\circ}C]$	$T_{j,max}[^{\circ}C]$	$\Delta T_j[K]$	$t_{on}[s]$	$t_{off}[s]$	$I_{L,ave}[A]$
1	40	150	110	21	84	28

After ca. 3800 cycles, investigations of the failure parameters have shown that two diodes (D4 and D6) exhibit no blocking capability. The crack of the chip observed in the analysis of D4 after test (Figure 12) clarifies this effect.

Till ca. 22000 power cycles, no further failures were registered and test was stopped because no reasonable accurate failure forecast is possible with the achieved failure data.

A typical behaviour of the diodes under test is shown in figure 13. A slightly increasing tendency of  $V_F$  and  $T_j$  can be observed, however the failure criteria are not immediately fulfilled.

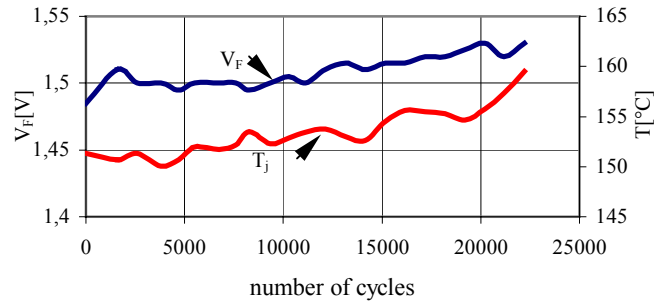


Fig.13: Power cycling test of copper based, transfer molded diodes for  $\Delta T_j=110K$

## V. STATISTICAL ANALYSIS

For the statistical analysis we applied Weibull distribution, which is widely used referring to reliability considerations. Weibull analysis provides reasonably accurate failure forecasts even with small sample sizes. Furthermore, it provides a simple and useful graphic plot ; the horizontal scale is a measure of life aging parameters (i.e. number of cycles); the vertical scales are the probability density  $f(x,\alpha,\beta)$  and cumulative percentage failed  $F(x,\alpha,\beta)$  defined as follows [7],[8].

$$f(x,\alpha,\beta) = \frac{\alpha}{\beta^\alpha} \cdot x^{\alpha-1} \cdot \exp\left(-\left(\frac{x}{\beta}\right)^\alpha\right) \quad (2)$$

$$F(x,\alpha,\beta) = 1 - \exp\left(-\left(\frac{x}{\beta}\right)^\alpha\right) \quad (3)$$

The Weibull slope ( $\alpha$ ) indicates which class of failure is present. An  $\alpha$  lower than 1 indicates the system or the samples are more likely to fail early and become more reliable as the aging parameters increases. At  $\alpha=1$  failures occur independent of aging parameter and an  $\alpha$  value higher than 1 indicates wear-out failures. The characteristic life  $\beta$  is defined as the age at which 63,2% of the units will have failed [8].

The Weibull parameters  $\alpha$  and  $\beta$  of the test results were obtained using the Maximum Likelihood Estimation method [9].

A statistical analysis of PC1, PC2 and PC3 was executed. Figures 14, 15 and 16 summarise the Weibull analysis.

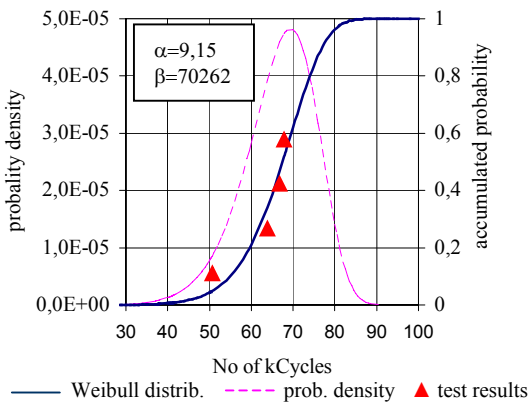


Fig.14: Weibull analysis for  $\Delta T_j=105$  K

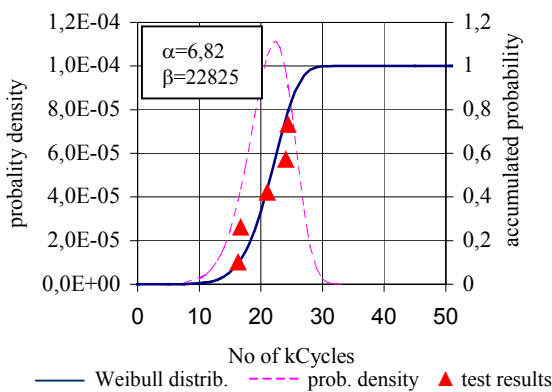


Fig.15: Weibull analysis for  $\Delta T_j=130$  K

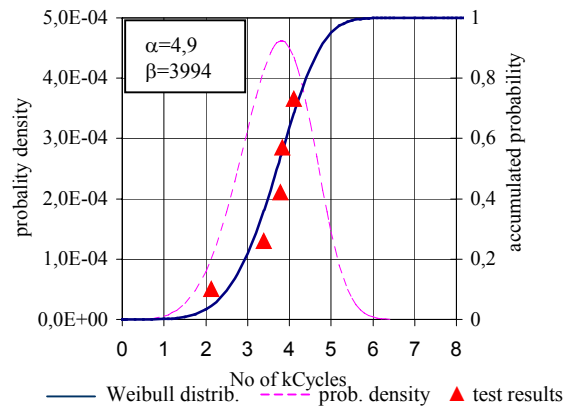


Fig.16: Weibull analysis for  $\Delta T_j=155$  K

A statistical evaluation of the copper based housings is not possible. Obviously, in them occur cracks in the volume of the semiconductor leading to failure in a medium time scale, sample which are not affected show an approximately one decade longer time to failure.

## VI. EVALUATION OF RESULTS

The following diagram presents a comparison between the results achieved in the test of the DCB based components at end-of-life failure probability for 50% from the Weibull analysis and an extrapolation of the LESIT results with standard modules.. Included in the comparison are the results achieved during the evaluation of advanced power modules based on a pressure contact design without base plate (SKiM) [3]. These modules consist of the same layers as Fig.1, but the compound material is replaced by a soft silicon gel. All test results are compared for test condition  $T_{j,min}=const=40^\circ C$ . DCB based, transfer molded components exhibit 10 to 12 times higher power cycling capability at temperature swings between 110 K and 155K compared to extrapolation of the LESIT results.

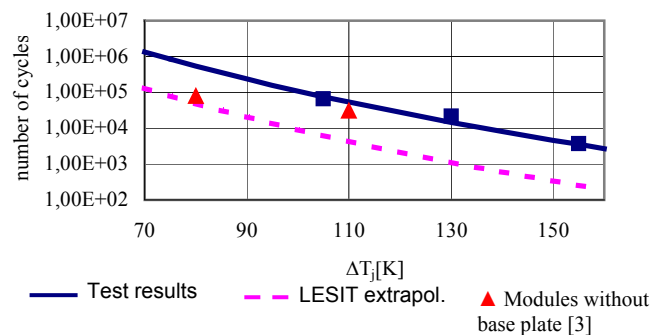


Fig.17: Comparison between transfer molded DCB based components, modules without base plate[3] and extrapolated LESIT results to the condition  $T_{j,min}=const.=40^\circ C$

A fit of the results allows the calculation of the power cycling capability of the DCB based transfer molded components. The exponent  $\alpha$ , which describes the decrease of cycle-to-failure with increasing temperature swing is -4,67 compared to -5,039 for base plate module and the constant A is 650790 compared to 302500 in LESIT equation (1). It must be respected that the results are only for temperature swings ( $\Delta T_j$ )  $\geq 110$  K.

Mechanical stress originating from mismatch of thermal expansion coefficients of silicon and copper lead frame can be identified as failure cause in the test of copper based, transfer molded devices. It must be respected that the used semiconductor chips with an area of 63 mm<sup>2</sup> are comparatively large for this type of housings. For a smaller die size, better results are expected.

## VII. CONCLUSION

The DCB based transfer molded components show at high temperature swings a higher power cycling capability than standard modules with base plate. They promise to fulfil the automobile standard AEC-Q101 at  $\Delta T_j > 130$  K.

Regarding the analysis of the components after test, supported by the end-of-life failure mode of PC2 and PC3, one can assume that the compound material decelerates the bond wire lift off which clarifies the high power cycling capability of the assembly technology.

The result of testing copper based, transfer molded diodes led to the assumption that this packaging technology is unsuited for applications with temperature swings in the range of 110K, if chips large chips, e.g. with area of 63 mm<sup>2</sup> or more, are used.

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