Double-Sided Low-Temperature Joining Technique for Power Cycling Capability at High Temperature

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Keywords

«Packaging», «Power cycling», «Reliability», «Thermal stress»

Abstract

There is a demand for higher junction temperatures in power devices, but the existing packaging technology is limiting the power cycling capability if the junction temperature is increased. Limiting factors are solder interconnections and bond wires. With Replacing the chip-substrate soldering by low temperature joining technique, the power cycling capability of power modules can be increased widely. Replacing also the bond wires and using a double-sided low temperature joining technique, a further significant increase in the life-time of power devices is achieved.

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 electronics will move under the hood [1], the cooling water temperature is specified to < 125°C, the demand to the max. junction temperature of devices is min. 175°C, better 200°C. The automotive standard AEC-Q101 stipulates that power components must withstand 5000 power cycles at temperature swings higher than 100K . Silicon devices for moderate voltages up to 200V would allow junction temperatures up to these ranges. GaAs and SiC devices can be operated at junction temperatures up to 250°C and more. But the standard packaging technology is limited to junction temperatures of approx. 150°C. The restricting reason is temperature and power cycling-capability. The Low Temperature Joining Technique (LTJT) promises to be a cogent solution to these problems [2].

II. Limits of Existing Technologies

As a reference for the power cycling capability of standard power modules, the results of the LESIT project shall be used. IGBT modules with base plate have been power cycled at different temperature swings [3]. A fit of the results can be summarised in the following empirical rule:

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

(N_f= number of cycles to failure; k_B = Boltzmann-constant ; E_a = activation energy = 9,891.10^{-20} J;
A = constant=302500 $K^{-\alpha}$; α = constant =-5,039; T_m = medium junction temperature [K] [4])

The power cycling capability depends strongly on $T_m = T_{j,min} + \Delta T_j/2$ and on the temperature swing ΔT_j. For increased ΔT_j at constant $T_{j,min}$ of 40 °C, the extrapolation of the LESIT results is depicted in Fig.1, demonstrating the decrease of number of cycles to failure (N_f) with increasing ΔT_j.

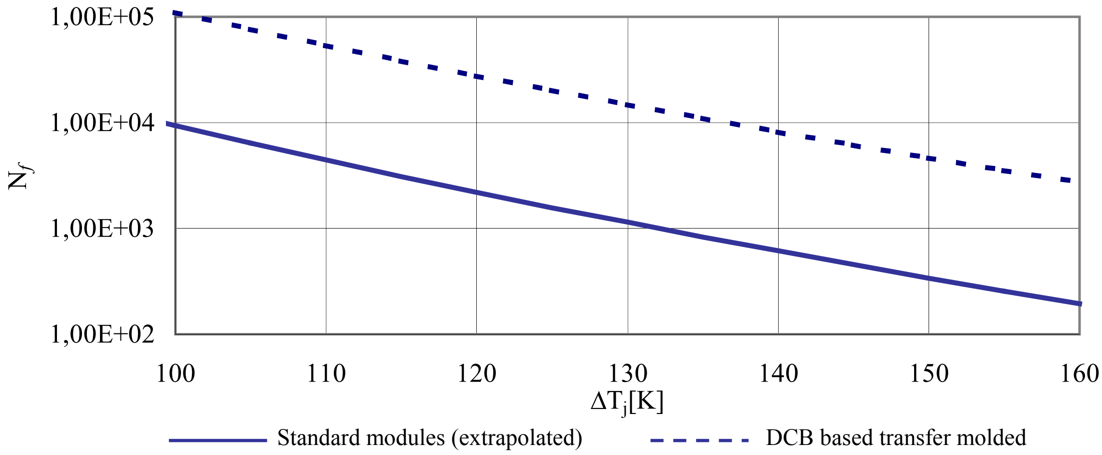

Fig. 1: Power cycling reliability of power modules ($T_{j,min}$ = constant= 40°C)

Since the completion of LESIT project in 1997 standard modules have been improved and new technologies have been implemented. For example, advanced power modules based on lead-free, Sn/Ag solder alloy cycled at ΔT_j = 60 , 80 and 110 K have shown a power cycling life-time by factor of about 4-10 times higher than the results to expect according to equation (1). The improvement is supposed to be due to an improved solder layer [5].

As a further example, the extrapolated power cycling reliability of DCB based transfer molded components according to results of power cycling tests at increased temperature swings are also shown in Fig.1. These components have shown a power cycling capability approx. 10 times higher than expected from extrapolation of results of standard modules. Modified values for the calculation of the power cycling capability of this housing are given in [6]. In these devices, the molding compound seems to hinder the lift-off of the bond wires even if the interconnection is deteriorated. But transfer molding is not easy to be realized in power module fabrication technology.

The LESIT-result [3] is still the reference to evaluate the reliability of power modules, it will be used to compare results but it must be kept in mind that different manufacturers have improved the power cycling capability significantly since the LESIT project. For example the introduction of protective coatings for wire bonds and AlSiC as base plate material has improved the reliability of power modules especially for traction applications [7]. The demand for higher power density of converters and higher temperature requires further improvement in power cycling capability [8].

III. Main Failure Mechanisms of Present Interconnection Technologies

The most important failure mechanisms encountered in modern power devices as result of power and thermal cycling are bond wire lift-off and solder joint degradation.

Bond Wire Lift-off: Bond wire lift-off is one of the most observed failure mechanisms affecting bond wires of nowadays high power devices subjected to thermal and power cycles. To a large extent it occurs because of the high mismatch of thermal expansion coefficient (CTE) between the aluminum wires (22 ppm/°C) and silicon chip (3ppm/°C) and leads finally to total interruption of the electrical connection from chip to the output pins . Bond wire lift-off can be retarded by bond-wire coating e.g. [9], but still constitutes a main restriction of power cycling capability.

Solder Joint Degradation: This failure mechanism is associated with the thermomechanical fatigue of solder layers between chip and DCB substrate and in power modules with base plate additionally between DCB substrate and base plate. Degradation in the solder layers deteriorates the removal of the heat dissipated within the chip which leads to an increase of the thermal resistance of the device. Solder layer degradation seems to play a significant role as a dominant failure mode in power cycle tests at ΔT_j>=110K [5][6]. Chip solder joint degradation became a concern for power module designers especially after the increase of bond-wire reliability achieved in the last years [10].

IV. The Low Temperature Joining Technique (LTJT)

Already 20 years ago the Low Temperature Joining Technique (LTJT) was discovered by Schwarzbauer [11] as an alternative for joining of large area silicon devices with molybdenum plates. Nowadays this process is applied in production of high power thyristors and diodes[12]. The joining technique is based on sintering of sub-micro silver flakes. The process is carried out at temperatures above 220°C and a pressure of about 40 MPa during one minute in air. The surfaces of the parts to be joined have to obtain an oxide-free metal finish such as gold or silver. The sintered silver layer exhibits typically a thickness of 15µm and a porosity of 15%. To investigate its properties free standing LTJT-foils were produced. Fig. 2 shows a broken edge of such a foil. In the upper part the smooth surface can be seen while the broken material in the lower part is characterized by the black holes causing porosity and elongated tear-off ridges as result of the fracture.

The LTJT-layer exhibits excellent thermal conductivity of about 250 W/m.K, electrical conductivity of 40MS/m and mechanical stability of 150 N/mm² which correspond to the values of pure silver [13] taking into account the porosity. The high melting point of silver (961°C) in comparison to soft solder yields high stability and reliability of the joining layer.

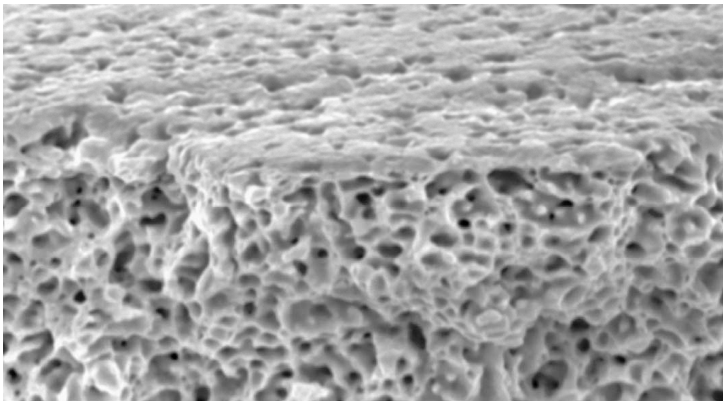

Fig. 2: Sintered foil of LTJT in SEM. (The width of the picture corresponds to about 25µm)

The goal of the presented work is to investigate whether the weak points of state-of-the-art set-ups can be eliminated using LTJT. The test sample of double sided LTJT consists of a diode chip mounted on a DCB-substrate as sketched in Fig. 3. The wire-bonds were replaced by two silver stripes of 1mm width and 100µm thickness. LTJT requires oxide-free metallization of surfaces to be joined. Thus the DCB-copper was gold plated. The cathode side of the diode already exhibited silver metallization. On the anode side an additional gold layer was evaporated. A silver powder layer was applied to the DCB-electrodes and to the anode as can be seen as light areas in Fig.3. All joints – diode to DCB, stripe to diode and stripe to DCB – are produced in a single press process at about 40 MPa, 250°C within one minute.

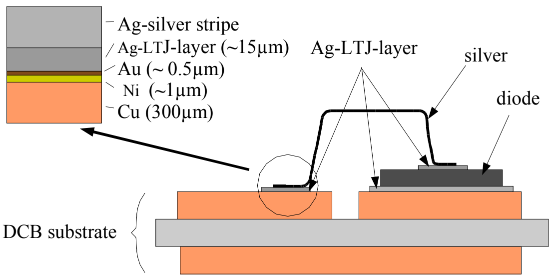

Fig. 3: Cross section of the test set-up

V. Combining LTJT with an Industrial Packaging Platform

To investigate the power cycling capability of LTJT, the technology was integrated in a standard low power module package. The EASY 1 package of *eupec* was selected [14]. As shown in Fig.4/left, one diode was placed in a standard DCB layout.

Fig. 4: Test set-up with double-sided LTJT (left: diode on DCB / right: finally packaged)

For comparison, a test setup is realized with one-sided LTJT followed by an aluminum wire bond process. The assembly with 400µm wire bond thickness is shown in Fig.5. The other set-up with the double-sided LTJT as described in chapter IV is realized with the same DCB layout (Fig.4 left).

In the first step the LTJT was applied to mount the diode on the DCB respectively the diode with silver stripes on the DCB. After wire bonding of the one-sided LTJT assembly, sockets are soldered on the DCB for the pins, which are used to conduct the load current. A replacement of this soldering step with LTJT is conceivable with slight changes. Compared to the standard module, no potting silicone sealant was used for the one sided LTJT to ease the evaluations of test results. The packaging procedure was finished by mounting the plastic housing. The module itself is mounted with screw clamps and thermal grease on a heat sink.

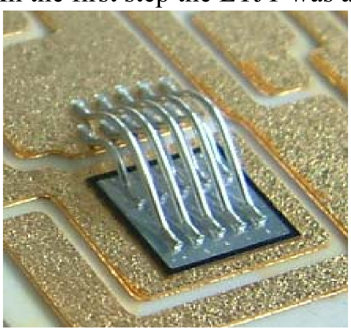

Fig. 5:One-sided LTJT with wire bonds

VI. Power Cycling Capability of One-Sided LTJT

Test Setup: In One-sided LT-joined devices only chip to substrate joint is produced by LTJT where the anode-side connections are established by standard ultrasonic wire bonding process. Devices under test (DUT) are five 50A/1200V freewheeling diodes and have been power cycled at ΔT_j=130K ($T_{j,max} \approx$ 170°C, $T_{j,min} \approx$ 40°C) simultaneously with the double-sided LTJT devices and under the same electrical and thermal conditions.

The heating current(I_L), $I_{L,DC} \approx$ 42A, is produced by a B2 rectifier bridge and heats the junctions to the desired maximal temperature ($T_{j,max}$) within the heating time (t_{on}).When an adjusted upper heat sink temperature ($T_{h,max}$) is reached, I_L is switched off and a cooling system consisting of electrical fans is activated till the minimal junction temperature ($T_{j,min}$) of ca. 40°C is reached again. Fig.6 shows a typical waveform of junction temperature (T_j) and heat sink temperature (T_h) during a power cycle.

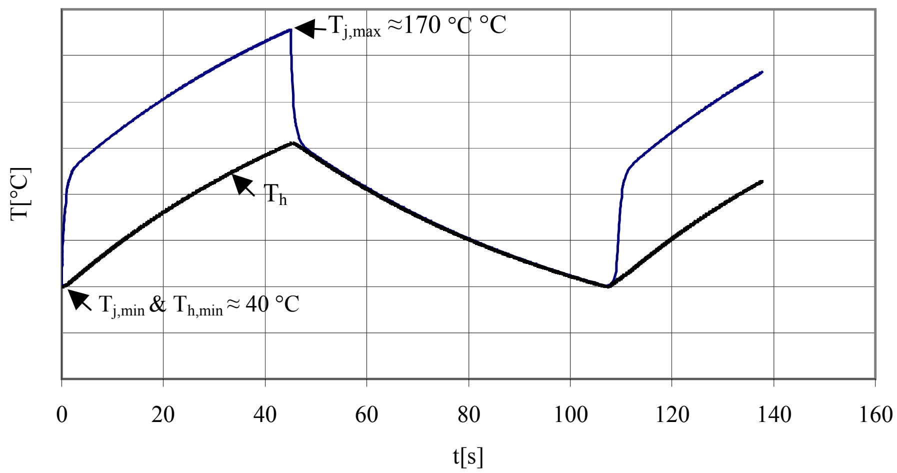

Fig. 6: Typical waveforms of T_j and T_h during a complete power cycle

The duration of the heating-up and cooling-down phases is directly controlled by reference upper and lower heat sink temperature measured 2mm underneath the central device. This control concept has the advantage to exclude influences of changes in ambient temperature or in cooling efficiency and at the same time it includes the effects caused by changes in the thermal resistance of the components or the heat sink interface [4]. T_j is measured indirectly by using the linear temperature dependency of the forward voltage (V_F) at a sense current of 50mA, which is ca. 1 $^o/_{oo}$ of the load current I_L, flowing continuously through the devices. Breaks of ca. 2ms exhibited in I_L allow to observe the behavior of V_F at sense current level and thus the measured virtual junction temperature.

Test Results: Testing of these devices was completed after the total failure of the last diode. The occurrence of the five failures was picked up by a control computer as the current flow was interrupted by the affected device. The first failure was registered after ca. 29460 cycles affecting diode G10; diode G3 failed lastly after ca. 44500 cycles; however the average value of $T_{j,max}$ of G3 amounted to 166 °C and thus it was the lowest, which could explain the relative long life-time of this device. Fig.7 shows the behavior of V_F at 40 A and its significant increase shortly before the affected device has reached its end-of-life.

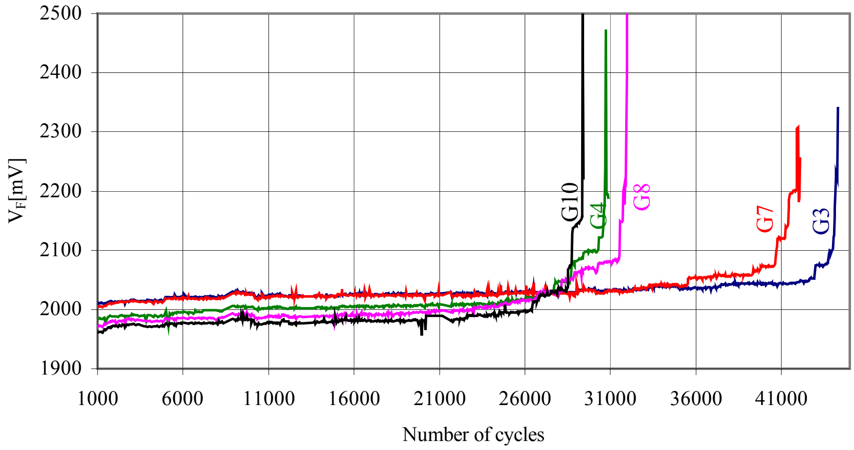

Fig. 7: Behaviour of V_F at 40 A (one -sided LTJ devices, ΔT_j=130K)

The behavior of $T_{j,max}$ is depicted in Fig.8 . No increase of $T_{j,max}$ was obvious till shortly before the diode reaches its end-of-life. The last increase of $T_{j,max}$ is due to the increasing of the dissipated power caused by increasing of V_F at load current I_L.

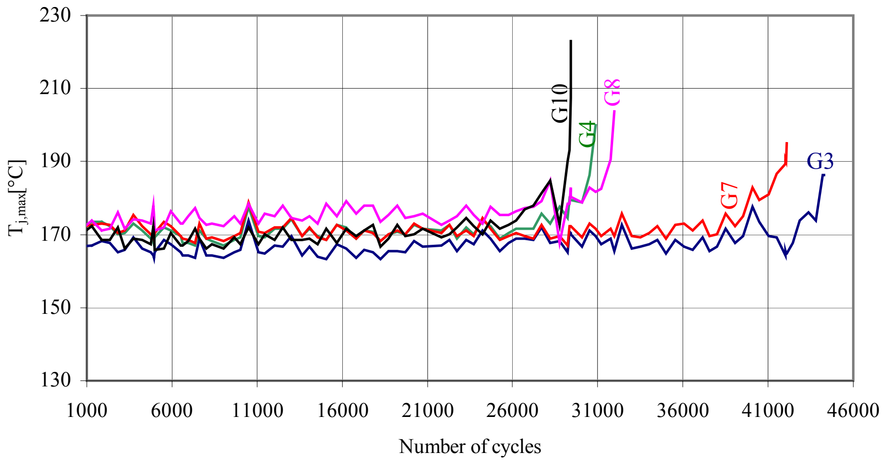

Fig. 8: Behaviour of $T_{j,max}$ (one -sided LTJ devices, ΔT_j=130K)

Failure Analysis: After nondestructive opening of the tested diodes, a SEM micrograph was employed for further investigation of failure mechanisms. The observed failures are exclusively related to bond wire and metallization aging and can be summarized in two failure modes.

a) Bond wire lift-off: This failure mechanism was widely observed affecting all tested devices. It could be predicted during the test by the increasing of the online sensed V_F at 40 A (Fig.7). As an example, Fig.9 (left) shows the completely lifted–off bond wires of diode N8 which has failed after ca. 32000 cycles. Furthermore, wire melting as a consecutive fault of wire lifting-off could be observed. Wire melting occurs after the significant increase of nominal current density of the survivor wires (1,5kA/ cm^2 in our test) accompanied by increased temperature after wire lifting offs have occurred (Fig.9- right).

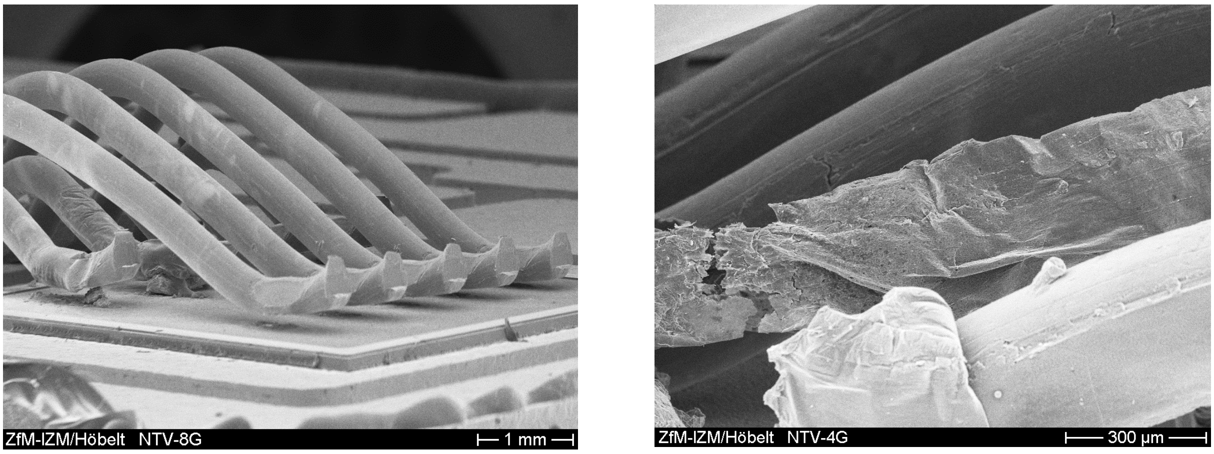

Fig. 9: Bond wire lift-off in diode G8 (left); Bond wire melting in diode G4 (right)

b) Aluminum Reconstruction: Wear out of the aluminum metallization by reconstruction could be observed too. Fig.10 shows the surface of the region adjacent to footprint of a lifted-off bond wire and the formation of grains and grain boundaries. Reconstruction of Al metallization could occur in conjunction with bond wire lift-off, which leads to non-uniformity of current density and local increase of temperature on the Al metallization [9] [15].

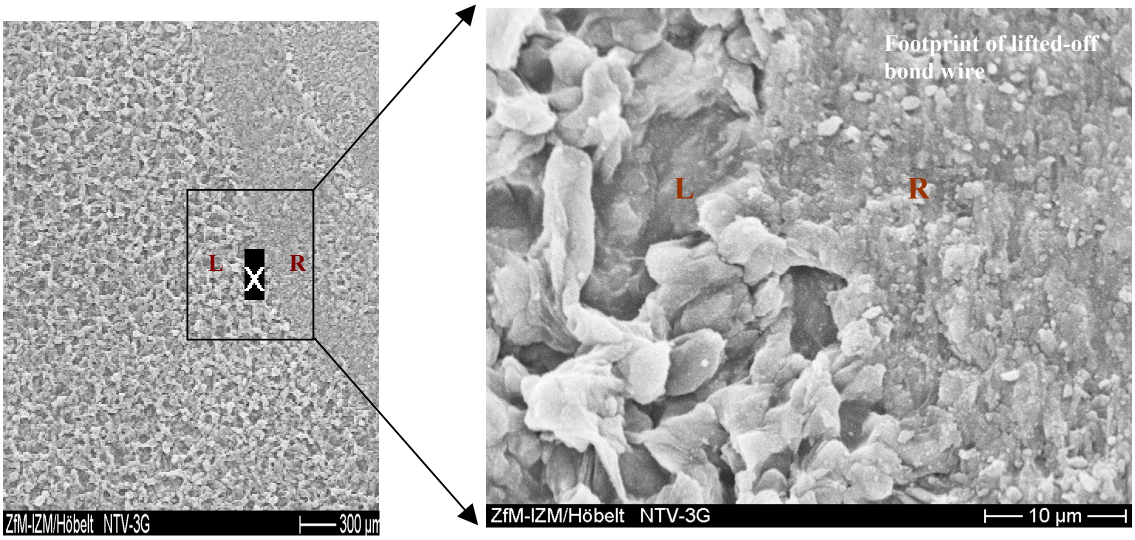

Fig. 10: Reconstructed metallization of diode G3 (Diode failed after ca. 44500 cycles)

VII. Preliminary Results of Power Cycling Test of Double-Sided LTJT

The Double-sided LT-joined devices were power cycled simultaneously with the one-sided LTJT devices on the same test bench and under the same electrical and thermal parameters. Devices under test are the same 50A/1200V freewheeling diodes. In these devices bond wires are replaced by silver stripes and all chip contacts, stripes-chip, stripes-DCB substrate, and chip-substrate, are realized by using the LTJT. Due to relatively high thermal resistance, $T_{j,max}$ of diode N3 was about 15 °C higher than the average value of $T_{j,max}$ of the other devices already at the begin of the test. Therefore the results of this device are not taken into account for the following analysis.

Till approximately 49000 cycles, no significant increase of $T_{j,max}$ was observed. Afterwards an increasing tendency of $T_{j,max}$ especially at N6 could be observed. To screen out any eventual aging of the efficiency of the thermal grease as the reason for increasing $T_{j,max}$, a fresh film of the same thermal grease has been reapplied after 56780 cycles. At the same time device N6 was removed from test to be examined more closely. At the moment of renewing of thermal grease and removing N6 its R_{thjh} had increased of ca. 14%, while the increase of R_{thjh} of N1 and N2 amounted ca. 7% and no significant increase of R_{thjh} could be observed at the other devices. However more investigations are necessary to clarify the increase of R_{thjh} definitively.

The behavior of $T_{j,max}$ is depicted in Fig.11. It is obvious that renewing thermal grease had an effect but the tendency of increasing $T_{j,max}$ has continued.

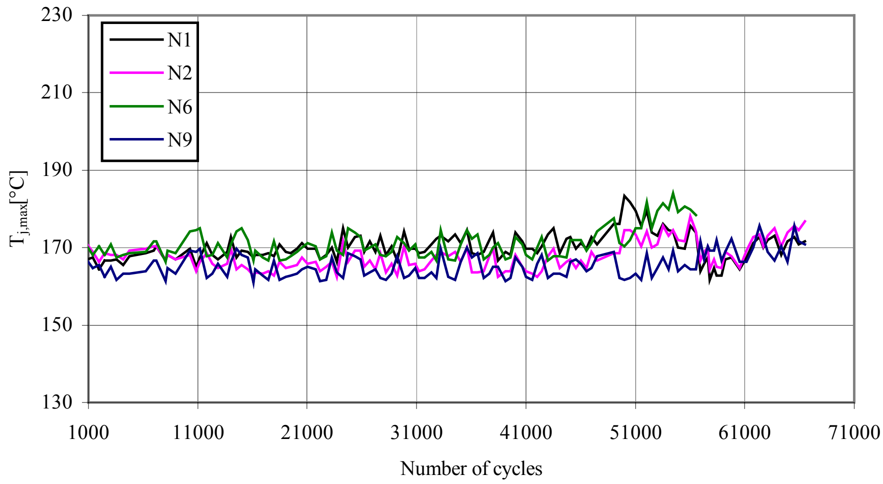

Fig. 11: Behaviour of $T_{j,max}$(double-sided devices , ΔT_j=130K)

The behaviour of the online sensed V_F at 40 A and $T_{j,min}$ (Fig.12) shows a maximum increase of 1,9% at N6 and N9 after ca. 56780 cycles. However, comparison between the measured V_F at 50 A and room temperature before the test and after 56780 cycles shows an increase of 0,9% at N6 and 0,5% at N9 and no noteworthy increase at the other devices. Thus, we consider the minimum increase of the online measured V_F as measurement error. The test was interrupted after ca. 66570 cycles and after failure of N2 which is definitively caused by lift-off of the pins for the outer connections, and not related to failure of the LTJT-interconnections.

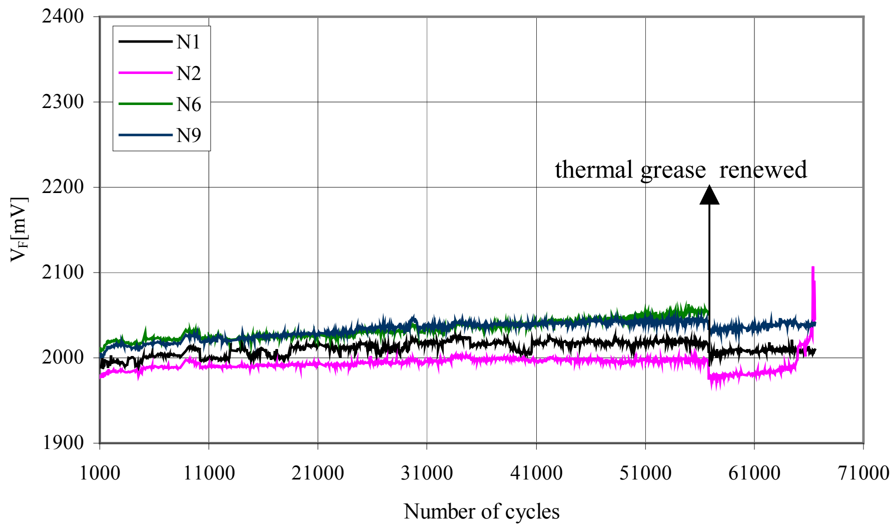

Fig. 12: Behaviour of V_F at 40 A (double-sided devices , ΔT_j=130K)

The tests of the remaining devices were in progress at the moment of preparing this paper. An accurate failure analysis will follow after finish of tests

VIII. Evaluation of Results

As shown in Fig. 13 the one sided LTJT devices show a power cycling reliability twenty times higher than the result expected by extrapolation of LESIT equation and two times higher than results of DCB based, transfer molded devices. Power cycling results of advanced *eupec* power modules with improved wire bond technology for high temperatures are included in the diagram. For the double-sided LTJT devices one can conclude that the power cycling capability is above 66 000 cycles at $\Delta T_j = 130°C$, since the failure was not caused by the LTJT interconnection. This means a factor of two higher than the one -sided LTJT devices, a factor 40 higher as the extrapolated LESIT results. The real power cycling capability of the new interconnection technology has to be investigated further since one seems to reach the limit of other module interconnections.

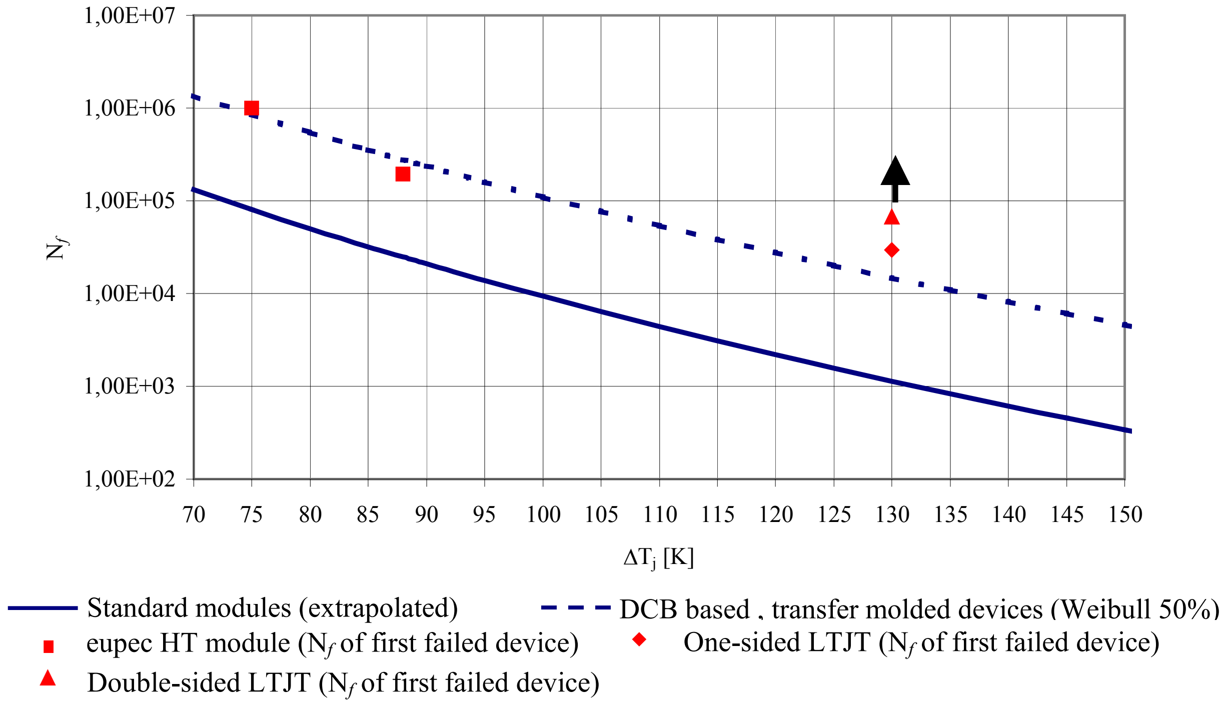

Fig. 13: Power cycling reliability of different packaging concepts

The most surprising result is the high improvement of the one-sided LTJT devices with replacement of solder by the LTJT. This may be explained by the assumption as described in [5], that for high ΔT_j the wire bond failure is a consequence of solder joint fatigue of the chip to DCB connection. With the application of LTJT this failure mode is eliminated and now the direct wire bond failure appears.

Earlier evaluation of one-sided LTJT at smaller ΔT_j of 88K [16] confirms this result. An improvement of 50 % power cycling capability until bond-wire lift-off has been found in this test. The higher improvement observed in this work may be caused by the different device and wire bond parameters used for the assembly, that is influencing the wire bond reliability. Additionally, assuming that the solder layer is the main reason of failures at higher temperature swings, it can be to expected that the improvement becomes higher with increased ΔT_j of 130K.

In the double sided LTJT the first failure has occurred after ca. 66570 cycles. However, the observed failure mode seems to be not related to the LTJT. Therefore, by replacing the remaining outer solder connections in the module by improved technology, a much higher power cycling capability is expected.

IX. Summary

The one-sided LTJT devices show a power cycling reliability at ΔT_j=130K twenty times higher than the result expected by extrapolation of LESIT equation for standard modules. Even if the improvement of standard modules since the LESIT project is taken into account, the increase of power cycling capability at high temperature swings is significant. Under these conditions, bond wires are clearly the weak point and their aging was the sole failure mechanism of these devices, permitting to determine bond wires, inherent lifetime. In the double-sided LTJT devices, silver stripes seem to withstand at least 66570 cycles without a significant aging. The main aging mechanisms of the double-sided LT joined devices are still to be investigated. Further tests are necessary to find the real end of life power cycling capability of the new double sided LTJT.

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