Power Cycling at High Temperature Swings of Modules with Low Temperature Joining Technique

R. Amro[1)]; J. Lutz[1)]; J. Rudzki [2)]; R. Sittig[3)]; M. Thoben[4)]
1) Chemnitz University of Technology-Germany
2) Kiel University of Applied Science-Germany
3) Technical University at Braunschweig-Germany
4) Infineon Technologies AG, Warstein-Germany

Abstract - **Standard packaging and interconnection technologies limit the maximal junction temperature (T_{jmax}) to about 150°C at present. This restriction is caused by the limited power cycling capabilities of Al bond wires and of soft solder joints. Important applications of power devices, however, require operating temperatures of 175°C or even 200°C.**

To evaluate the suitability of the Low Temperature Joining Technique (LTJT) for future module set-up, test samples were prepared and investigated. Already the replacement of only the chip-to-substrate solder joint (one-sided LTJT) improved the power cycling capability at ΔT_j=130K five times or at a ΔT_j=156K ten times compared to the expected capability of soldered and wire bonded devices at these conditions. Application of LTJT to top side chip connections also, i.e. additional replacement of bond wires by silver stripes joined by LTJT (double-sided LTJT), yielded a further increase of power cycling capability.

I. INTRODUCTION

New trends in industrial and automotive applications are requiring maximal junction temperatures ($T_{j,max}$) of up to 175°C or even 200°C. This demand can be fulfilled by Si devices for moderate voltages up to 200V and more. GaAs as well as SiC devices are suited for even higher operation temperatures. However; in most applications of power devices, the maximal allowed junction temperature is limited to 150°C. Main reason for this restriction is the decrease of power and thermal cycling capability of standard packages with temperature.

Already the effort of design engineers yielded clear improvements in power cycling reliability of Al bond wires and soft solder technology during the last decade. There are, however, experimental evidences that this technique will not open a path to high temperature applications [1]. Low Temperature Joining Technique (LTJT) promises to be a reliable alternative even at extreme thermal conditions.

II. PRINCIPLE OF LTJT AND DEVICES UNDER TEST

The LTJT is based on sintering of sub-micro silver flakes. The process is carried out at temperatures above 220°C and pressure of about 40MPa. 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 [2]. The LTJT layer exhibits excellent thermal and electrical conductivity (250W/mK and 40MS/m respectively) and tensile strength of 150N/mm^2 at 20°C [3]. The high melting point of silver (961°C) yields high stability and reliability of the joined layer.

The tested devices are 50A/1200V free wheeling diodes with two different interconnection concepts:

a) One-sided LTJT devices: In the one-sided LTJT devices, only the chip-to-DCB substrate joint is produced by LTJT whereas the top side connection is realized by Al bond wires with 300µm or 400µm wire thickness.

The internal layout of one-sided LT joined assembly with 400µm thick bond wire is shown in Fig.1.

Fig.1: Test Set-up of one-sided LTJT

b) Double-sided LTJT: In double-sided LTJT devices, bond wires are replaced by 1mm wide silver stripes and LTJT is applied to realize all device joints; namely chip-to-substrate; silver stripes-to-chip and silver stripes-to-DCB substrate [4].

Fig.2 shows the internal layout of double-sided LT joined diode.

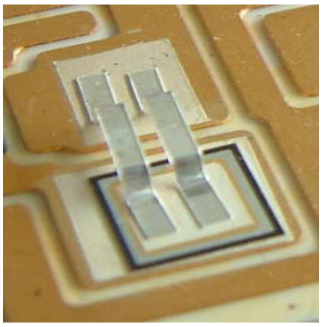

Fig.2: Test Set-up of double-sided LTJT

For performing the power cycling tests, the technology was integrated in a standard low power module package. The ***EasyPack1*** package of *Infineon* shown in Fig.3 was selected. Terminals for external connections are attached by solder joint on the DCB substrate. Replacing of these sole soldered joints by LTJT is conceivable with slight changes. To ease the evaluation of test results no silicon soft mold was used in one-sided LTJT.

Fig .3: Finally packaged LTJT device

III. TEST SET-UP AND MEASURING STRATEGY

The samples are mounted on a Al heat sink. The load current is generated by full-wave bridge rectifier and heats the devices up to the desired maximal junction temperature ($T_{j,max}$) within the heating time t_{on}. When the adjusted upper heat sink temperature ($T_{h,max}$) is reached, load current is switched off and a cooling system consisting of three electrical fans is activated till the lower heat sink temperature ($T_{h,min}$) is attained. The duration of heating and cooling phases is directly controlled by reference of the upper and of the lower heat sink temperatures which were measured 2mm underneath the centre device. This control concept has the advantage to exclude influences of changes in the ambient temperature and at the same time it includes the effects caused by changes in the thermal resistance of the components [5].

Measuring of the junction temperature is accomplished by using the linear temperature dependency of the forward voltage (V_F) at a sense current of 50mA (Temperature Sensitive Electrical Parameter method). To this goal the load current is interrupted during 2,7ms to measure V_F at sense current level and determine T_j.

IV. POWER CYCLING RELIABILITY OF ONE-SIDED LTJT

a) Test results at ΔT_j=130K

The most important test parameters are summarized in Table1.

Table1: Test parameters of power cycling test at ΔTj=130K

$T_{j,min}$[°C]	$T_{j,max}$[°C]	$I_{L,DC}$[A]	Heating time[s]	Cooling time [s]
40	170	42	44	65-85

The first device failure was registered after ca. 29460 cycles when load current flow was completely interrupted. As expected, the diode exhibiting the lowest average $T_{j,max}$ of 166°C failed as last one after ca. 44500 cycles.

The curves of on-line measured V_F at 40A and of $T_{j,max}$ are depicted in Fig.4. The significant increase of V_F indicates the forthcoming total failure of the devices due to lift-off of the bond wires. The maximal junction temperature ($T_{j,max}$) shows a stable behaviour till shortly before end-of-life of the affected device. At constant current the increase of V_F yields growing power dissipation which causes an increase of $T_{j,max}$.

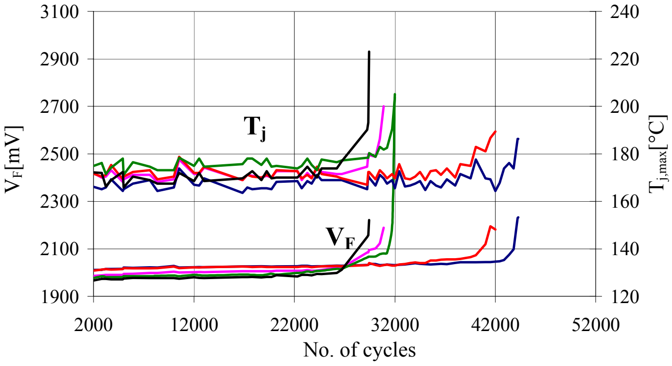

Fig.4: Behaviour of one-sided LTJT during power cycling test at ΔT_j=130K

Failure analysis: Scanning Electron Microscopy (SEM) was employed for further investigation of failure mechanisms. Bond wire lift-off affected all tested devices. A representative SEM image is shown in Fig.5.

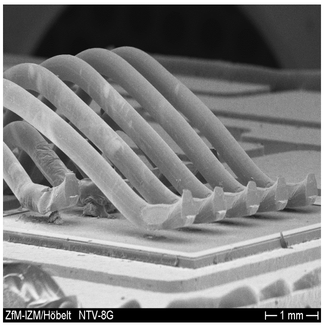

Fig .5: Bond wire lift-off of one-sided LT joined diode after 32000 power cycles

Wear out of aluminium metallization by reconstruction could be observed too. Reconstruction of Al metallization can occur in conjunction with bond wire lift-off, which leads to non-uniformity of current density and local increase of temperature on the metallization. Fig.6 shows the reconstructed metallization of DUT after ca. 44500 cycles (left) compared with the same metallization type in unstressed state (right).

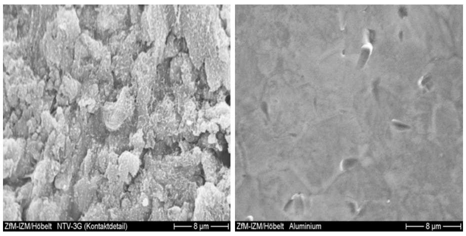

Fig .6: Reconstructed metallization of one-sided LT joined diode power cycled at ΔT_j=130K(left); unstressed metallization (right) (SEM image 4875x)

b) Test results at ΔT_j=156K

The most important test parameters are summarized in Table2.

Table2: Test parameters of power cycling test at ΔTj=156K

$T_{j,min}$[°C]	$T_{j,max}$[°C]	$I_{L,DC}$[A]	Heating time[s]	Cooling time [s]
40	196	42	57	75-83

The top side connections of these devices are performed by an advanced bonding process and with Al bond wires of 300µm wire thickness.

The increase of the on-line measured V_F is due to degradation of a remaining soldered joint because the whole module was faced extreme cycling as well which also led to the total failures of the devices. However, the increase of V_F of one device was observed to be caused by lift-off of some bond wires. Further behaviour of V_F, as depicted in Fig.7, and microscopic investigations supported these assumptions.

Due to the better cooling conditions at both ends of the heat sink, $T_{j,max}$ of outer devices were slightly reduced and amounted at test begin to 185°C and respectively 191°C. A separate increase of T_{jmax} of these devices was not possible without overstressing the devices mounted at the centre of the heat sink. Test was started with nominal $T_{j,max}$ of 196°C. An increase of $T_{j,max}$ was only observed in combination with increased dissipation power due to increase of V_F. For the sake of clarity and reasonable scaling, Fig.7 shows the behaviour of V_F and $T_{j,max}$ during the test of three devices only. However these represent typical behaviour for the other diodes.

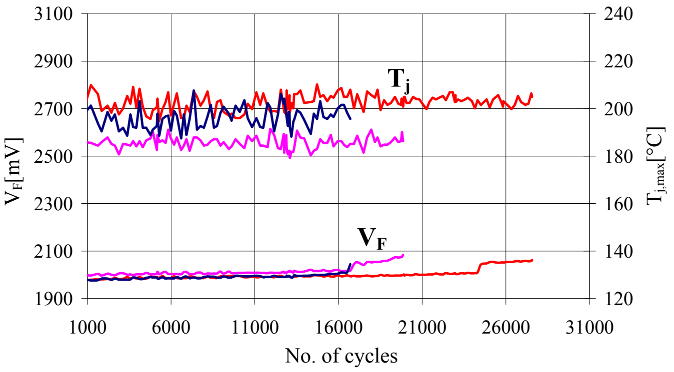

Fig.7: Behaviour of one-sided LTJT during power cycling test at ΔT_j=156K

Failure analysis: At one device a clear weakening of the connection of two bond wires was observed (Fig.8-left). This device failed totally after 16800 power cycles due to degradation of remaining soldered joints in the package. Shear tests of the bond wires revealed that the strength of the wire bonds is decreased by about 60% to 80% compared to unstressed reference device. The decrease for bonds connected to the Cu metallization is between 30% to 65%. Furthermore, a high graded reconstruction of the metallization could be observed. Fig.8-right shows the reconstructed metallization with grains of about 5µm diameter after 16800 cycles.

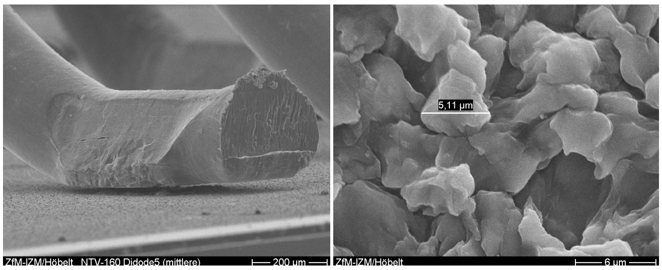

Fig .8: Bond wire lift-off (left) and reconstruction of metallization of LT joined diode power cycled at ΔT_j=156K after 16800 power cycles

V. POWER CYCLING RELIABILITY OF DOUBLE-SIDED LTJT

The double-sided LT joined devices were connected in series with the one-sided LTJT power cycled in the first test. Thus, the thermal and electrical parameters of the test are identical to the parameters summarized in Table1.

Till ca. 49000 cycles, no significant increase of $T_{j,max}$ was obvious. Afterwards an increasing tendency of $T_{j,max}$ was observed. To screen out any eventual aging of the efficiency of the thermal grease as reason of the increase of $T_{j,max}$, a fresh film of the same thermal grease was applied after 56780 cycles. At the same time the device with the maximal increase of $T_{j,max}$ was removed from the test for closer investigations. At the moment of removing the device, the increase of it's $R_{thj\text{-}h}$ amounted approx. 14%. Off-line measurements of V_F at room temperature have confirmed that the slightly increase of the on-line measured V_F of maximal 0,9% is probably due to measurement error. Test was stopped after ca. 66570 cycles after the total failure of one device which could be definitively identified as not to be correlated with the LT joints but with a remaining solder connection of the tested devices. The behaviour of the devices during test is depicted in Fig.9.

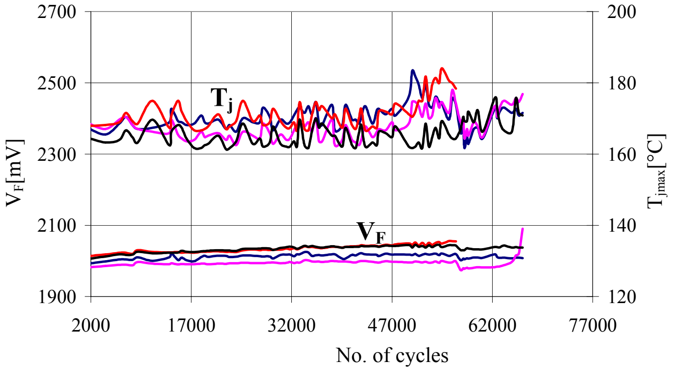

Fig.9: Behaviour of double-sided LTJT during power cycling test at ΔT_j=130K

Failure analysis: Ultra-sound microscopy has shown that no degradation of the LTJT layers is obvious. Fig.10 shows the LTJT layer between chip and DCB substrate before (left) and after (right) the test. The images are from the device at which the maximal increase of $R_{thj\text{-}h}$ was observed.

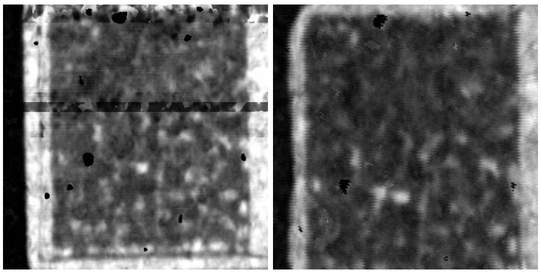

Fig.10: LTJT layer chip-substrate before (left) and after (right) 56780 power cycling at ΔT_j=130K: No degradation is obvious

However, peeling of Cu metallization from the DCB substrate of some devices could be detected (Fig.11). This mechanical aging of the DCB substrate causes the increase of the thermal resistance of double-sided LTJT during the test.

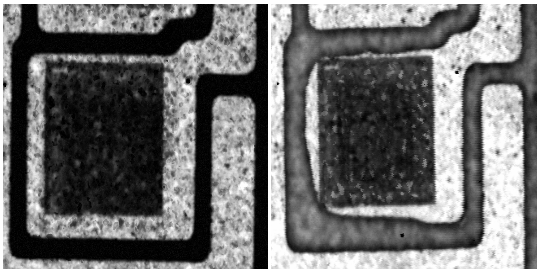

Fig.11: DCB substrate of double-sided LT joined diode before (left) and after 66570 power cycles (rights) at ΔT_j=130K: Peeling of the Cu metallization

VI. EVALUATION OF RESULTS

One-sided LTJT shows at ΔT_j=130K a power cycling capability being five times higher than could be expected for state-of-the-art of standard soldered modules. By application of LTJT for chip-substrate connection combined with an improved wire bonding process, a significant improvement of power cycling capability at ΔT_j=156K could be achieved. Clear weak points of one-sided LTJT are the Al bond wires and the Al metallization. The surprising high power cycling reliability of one-sided LTJT at high temperature swings can be explained by the assumption that at high ΔT_j the fatigue of solder layers is the dominant failure mode and its thermal consequence accelerates bond wire lift-off and reconstruction of metallization. With application of LTJT this failure mode is eliminated and now the aging of bond wires and metallization can directly be observed.

Samples with double-sided LTJT show at ΔT_j=130K a power cycling reliability being at least two times higher than that of one-sided LTJT devices. The sole failure is not correlated with LT joints but with a remaining solder connection in the assembly. Behaviour of V_F during the test and subsequently ultra-sound images have shown that silver stripes withstood 66750 cycles (till test stop) without degradation. However some peeling of Cu metallization of the DCB substrate was observed. Fig.12 shows the power cycling reliability of LTJT compared to that of existing packaging concepts. Even if the improvements in the module technology in the last ten years is considered, the reliability of LTJT is significant.

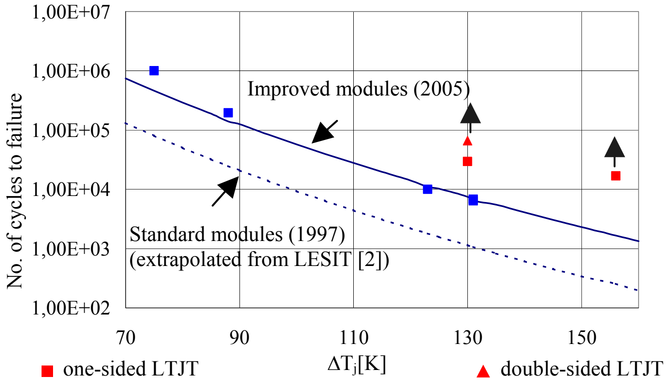

Fig.12: Results of power cycling tests of LTJT compared with different technologies

VII. SUMMARY

One-sided LTJT shows a power cycling reliability at ΔT_j=130K and 156K five to ten times higher than the results expected from state-of-the-art of soldered standard modules and twenty to seventy times higher than expected from extrapolation of lifetime model for standard power modules at 1997 [2]. The limit of power cycling lifetime of double-sided LTJT at ΔT_j=130K could not be reached till 66570. Further tests are necessary to determine the real power cycling reliability of double-sided devices at high temperature swings.

The lifetime of the one-sided LT joined devices was limited by aging of the Al bond wires and the reconstruction of the Al metallization. Furthermore, mechanical aging of the DCB substrate by peeling of the Cu metallization seems to be a lifetime limiting effect. The use of improved ceramics can reduce this mechanism significantly [6]. Countermeasures to improve the reliability of metallization and bond wires like using of polymeric coating [7] could be used and their efficiency at high temperatures should be evaluated.

From the test results, it can be concluded that bond wires are not the real weak point at high temperature swings but standard solders and the thermal consequence of its fatigue on the interconnection layers. LTJT promises to fulfil the power cycling requirements at temperature of 200°C.

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