

Further Improvements in the Reliability of IGBT Modules

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Abstract- This paper gives a survey of the measures and the resulting improvements of IGBT module reliability reached by eupec during the introduction of IGBT high power modules.

INTRODUCTION

Since their market introduction in the beginning of 1995, eupec IGBT high power modules (IHM) got a quick access to several applications in the lower and medium voltage range because of their obvious advantages with regard to controllability, isolation and mounting.

When introducing high voltage 3.3 kV IGBTs (IHV) intended for the upper power range and traction applications additional demands are made to the electrical and mechanical characteristics of the modules. These growing requirements will be met by continuous progresses in the module design in the areas of substrate, bond wire and base plate technology, partial discharge immunity as well as improvements of the electrical chip characteristics.

POINTS OF IMPROVEMENT

Bonding

A high power IGBT module comprises approx. 450 wires together with 900 wedge bonds. For many years the reliability of this contact technology has been a concern especially for traction applications. Considerable work, e.g. in the LESIT-program, has been concentrated on accelerated power cycling tests, analysis of failure mechanisms and improvements in bonding technology. Disconnection of bond wires due to heel cracks, bond lift-offs, reconstruction of Al-metallization on the chips and corrosion of wires were step-by-step identified as reliability limiting weak points. Development activities on

- composition of wire
- shape of bonding tool
- bonding parameters
- metallization of chips and leads
- protective coatings

have led to considerable improvements in the reliability of the bond contact. Test results of short time power cycling on IGBT modules with up to 24 paralleled IGBT chips are shown in Fig. 1, comparing the number of cycles versus the junction temperature swing. The „IHM

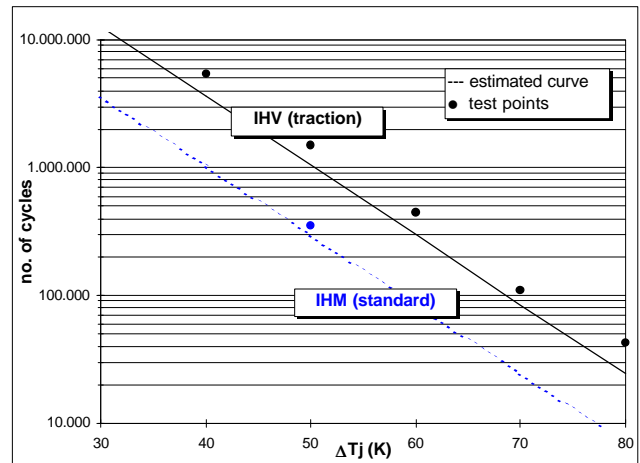


Fig. 1. Short time power cycling

(standard)“ modules are designed for the needs of standard industrial applications while the curve labeled „IHV (traction)“ represents the results for modules applying all the above mentioned improvements, therefore fulfilling even the severest requirements of traction applications. These modules are available in the traction relevant IGBT voltage classes 1700 / 2500 / 3300 V.

The criteria for failure was an increase of forward voltage by more than 5%. The tests with temperature swings of 40°C, 50°C and 60°C have been performed to get reliable data for practical operating conditions. The runs at $\Delta T_j = 70^\circ\text{C}$ and 80°C have been made to gain information about accelerating factors.

The test at $\Delta T_j = 40^\circ\text{C}$ with 20 modules under test took one year while the run at $\Delta T_j = 60^\circ\text{C}$ could be finished within 4 weeks. It is worthwhile to mention that these two tests were carried out with the same production lot of IGBT modules on the same test equipment controlled by the same team. Diode parts and IGBT parts of high power modules were tested separately.

Concluding from the technological analysis of failed modules out of the test programs it can be stated: there are no more bond wire lift-offs and no corrosion of the wire to be found. The failure mechanism has been changed throughout. Even after 9 million cycles all bond wire connections to the IGBT chips are still good. An additional overload test of the IGBTs with 8 kA subsequent to power cycling was passed without failure.

Base plate

The use of copper as base plate material is common for its well known advantages with regard to high thermal conductivity, easy mechanical handling, galvanic plating and adequate pricing. Disadvantages are non reversible changes of mechanical properties above 300°C and the mismatch of the coefficient of thermal expansion (CTE) to the ceramic substrate.

The soldering between substrate and base plate is therefore a failure source. Because of different CTEs of the materials thermal stress occurs and generates mechanical strain on the solder. Repetitive, heavy load cycling will create solder cracks and therefore an increase of the thermal impedance between chip and base plate.

Efforts have been made to mitigate the bimetallic effect of the soldered system metal / ceramic by an adequate shaping. A machined convex bow as shown on the right side of Fig. 2. clearly improves the heat transmission between base plate and heat sink.

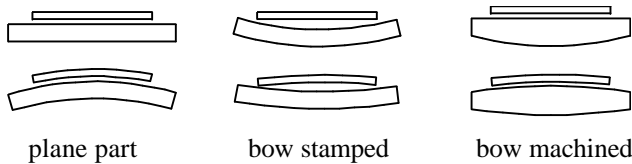


Fig. 2. Bending of the system metal / ceramic before (top) and after (bottom) soldering

A relatively stiff material with low deviation of its CTE to the ceramic would solve both described problems. As seen in Fig. 3 the metal matrix compound (MMC) material Al/SiC offers an extreme stiffness and a CTE close to that one of the AlN ceramic (7.3 ppm/K).

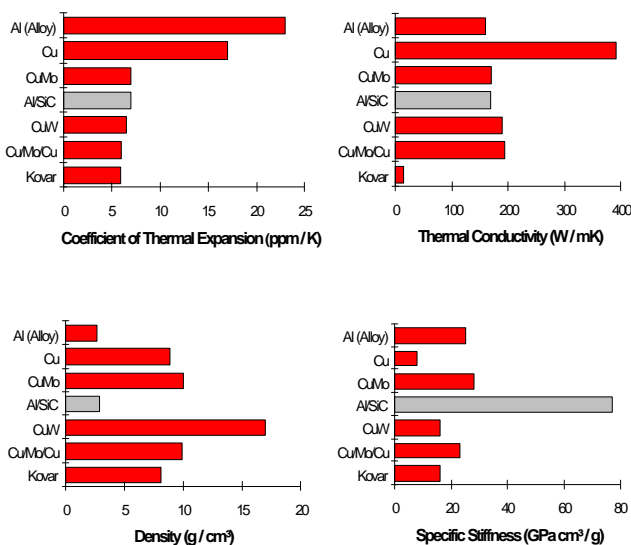


Fig. 3. Selection criteria for base plate materials

The divergence of approximately 50% to the thermal conductivity of copper is obvious but not as significant as it might look at first glance. The thermal resistance of the base plate compared to the total thermal resistance of the module is in the range of only 20%. When further considering the renunciation of additional intermediate layers when using CTE-matched materials, the increase is even less. Furthermore the diminished bimetallic effect results in a well-balanced contact surface to the heat sink.

The most outstanding advantage can be seen in the gain of reliability. At highly accelerated cycling tests with $\Delta T_c = 80$ K the solder layer between copper base plate and ceramic showed a delamination at the edges of the substrate after 4000 cycles. With the new Al/SiC base plate and under the same test conditions we have reached 20.000 cycles so far without any signs of delamination. Tests will be continued to define the exact factor of the reliability improvement.

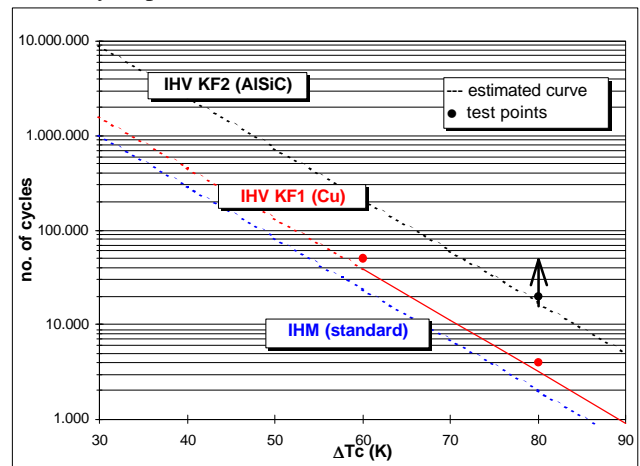


Fig. 4. Load cycling capability

Fig. 4 shows this gain of reliability when comparing the high voltage IGBT traction module „KF1“ (Cu base plate) with the new generation „KF2“ (AlSiC base plate).

Partial Discharge

To estimate the lifetime of the insulation without the need of high voltages as in the dielectric test, the „partial discharge test“ has been introduced [1].

Partial discharge (PD) is a partial breakdown of the insulation material. An example for a PD source is a small void in ceramics. If the voltage exceeds the breakdown voltage of the gas included, a sudden flash-over discharges the void. The recharge can be measured. PD occurs when increasing the voltage beyond the inception voltage and it disappears when decreasing the voltage below the extinction voltage.

Following the development steps between 1995 and 1997 the partial discharge level of the 3.3 kV IGBT modules has been considerably reduced as shown in Fig. 5.

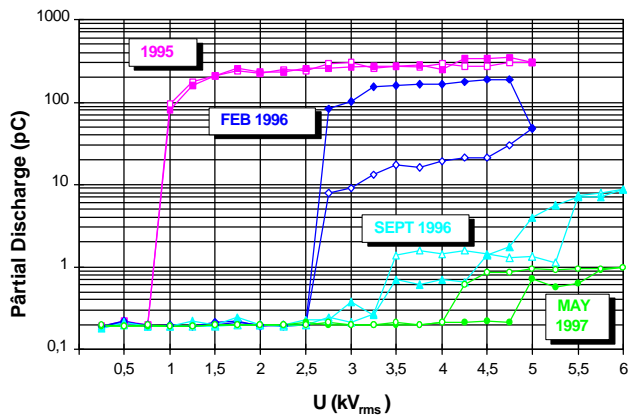


Fig. 5. PD-Improvements on 3.3kV IGBT Modules

In 1995 we started using DCB on 0.63 mm thick Al_2O_3 ceramics. We had the low inception and extinction voltages typical for this material and partial discharge values in the range of 200 to 300 pC. We limited the voltage during these first test runs on complete modules to 5 kV_{rms}, 1 min. By changing the ceramics from Al_2O_3 to AlN in February 1996 the inception voltage was increased and the devices could meet the specification target 10 pC as per IEC 1287. Further improvements of substrates and silicone gel resulted in an even lower partial discharge. The 10 pC at 6 kV target was reached in September 1996.

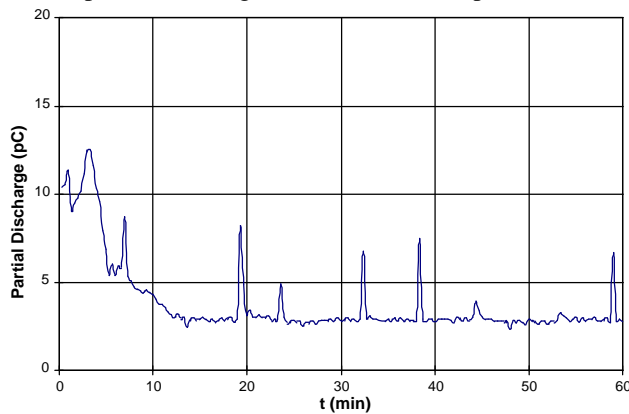


Fig. 6. Recording of PD-test of a 3.3kV IGBT module with enhanced insulation capability; test conditions: $U_p = 6$ kV_{rms}, $t = 60$ min.

In addition to the requirements of the IEC 1287-standard we have considered the behavior of the modules under long term high voltage stress. We recorded PD during a one hour test at a voltage $U_p = 6$ kV, see Fig. 6. PD decreased and was significantly lower than the required 10 pC.

Chip characteristics

In today's high power modules up to 24 chips are mounted in parallel. A prerequisite for a proper operation of these modules are an equal current sharing and a

homogeneous temperature distribution. This conditions can be reached by:

- rugged NPT chip technology
- narrow distribution of chip parameters
- a positive temperature coefficient of V_{cesat} .

Tests have been performed to clarify within which limits matching of chips is necessary.

In principle, matching is possible on single wafer level (all chips within a module from same wafer), on lot level (all chips within a module from same lot) and across all production lots (mixing chip lots in modules), of course with chips fulfilling proper data limits.

Statistic process control and practical experience have shown us that staying within the same chip lot during the assembly of modules results in reliable devices, even with 24 chips per device [2].

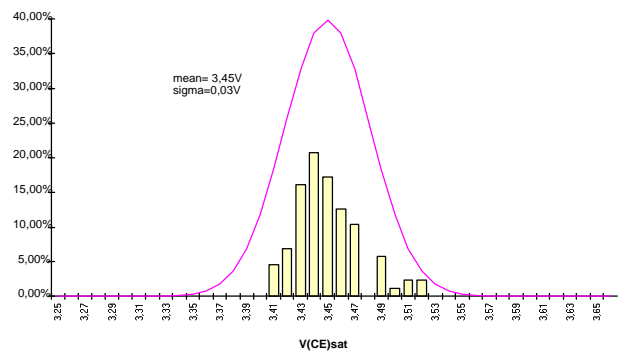


Fig. 7. Distribution of V_{CEsat} -values of IGBT chips of one lot (50 A, 3300 V); test conditions: $T_{vj} = 25$ °C, $V_{GE} = 15$ V, $I_c = 50$ A

As an example Fig. 7 shows the V_{CEsat} -distribution of the individual chips out of a certain lot, there are no chips outside the range of $3.45 + 0.09$ V (3 sigma). The practical consequence is that all these chips can be mounted without further selection in a series production.

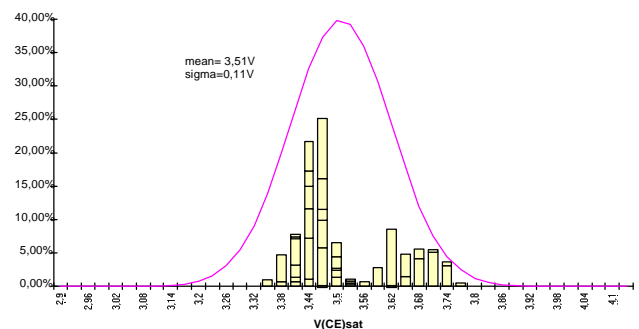


Fig. 8. Distribution of V_{CEsat} -values of high voltage IGBT modules of 8 lots (1200 A, 3300 V); test conditions: $T_{vj} = 25$ °C, $V_{GE} = 15$ V, $I_c = 1200$ A

Measuring the V_{CEsat} - values of ready mounted modules out of 8 different lots, as plotted in Fig. 8, we find, as expected, a wider distribution. This is due to differences

between the chip lots but not the result of parameter scattering within one individual chip lot.

CONCLUSION

As explained above, a lot of measures were taken to insure the reliability of the modules and to meet the customer's requirements. Due to the low number of devices under test, it is very difficult to predict a lifetime for the modules operated under field conditions only from the results of these accelerated reliability tests. First estimates, based on an operation under the following conditions:

- load current: 50% I_{nom}
- blocking voltage: 50% V_{ces}
- ambient temperature: 40°C
- operating: > 1000 h
- application class: N

resulted in a failure rate of below 500 FIT.

So far eupec has delivered more than 150.000 IHM and IHV IGBT modules to customers. High attention has been paid to the rejects from the customer and especially from the field. In tight cooperation with key customers detailed investigations of all failures have been performed.

With these new informations, based on more than 700 Mio. estimated hours of module operation, we can now expect a future failure rate for our high power modules of 50 FIT.

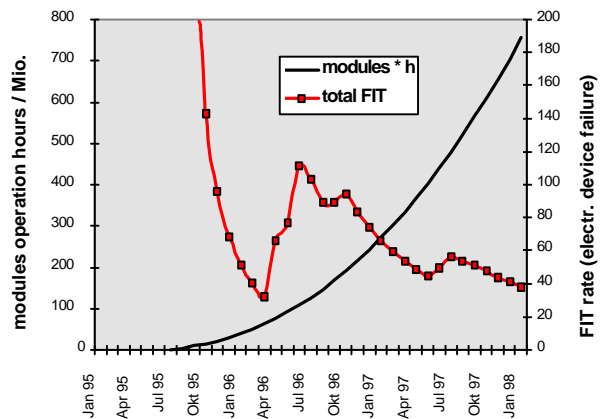


Fig. 9. Operation hours and resulting FIT rates

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- [2] K. Sommer, J. Göttert, G. Lefranc, R. Spanke, „Multichip high power IGBT modules for traction and industrial applications,“ Proceedings EPE 1997 Trondheim, pp. 1112-1116