High-Voltage Insulation Power Modules - System Design and Qualification

One of the substantial causes of reliability deficiencies in soldered-base power modules is the soldering between the substrate and the base plate. This is owing to the surface area of this interface, which is very large in comparison to other soldered areas, and the large mismatches between the Coefficient of Thermal Expansion of the insulator and the base plate materials. But not all failures can be attributed solely to this factor. Others such as wire bond lift-off, die attach failure, insulator cracking and power terminals detachment are main contributors. A real design for a cost-efficient module with no compromise in system reliability will be introduced here, where design reliability has been verified in accordance with industrial standards.

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IGBT power modules with soldered base plates are used in a host of applications. When designing these modules, the electrical and mechanical features of the components used, as well as the reliability levels stipulated by law and application requirements, must be achieved in a solution that is the optimum compromise between costs and benefits. It does not make sense to have excellent reliability in one single area because the service life of the module is not determined by one single factor. Such an approach may provide a high cost to benefit ratio that is justifiable in very few cases only. One of the most important causes of failure in these modules is solder degradation between the substrate (usually DCB) and the base plate [3,4]. This is not the only factor that contributes to failure [2,3,5,6,7]. It is imperative that every failure mechanism be taken into account. What has to be pointed out here is the fact that thermal stresses acting on the DCB-base plate interface are dependent on the substrate dimensions. In the design proposed, the DCB is split into a number of smaller parts to improve reliability and lower costs. This approach is then verified in the design and qualification process for a real power module.

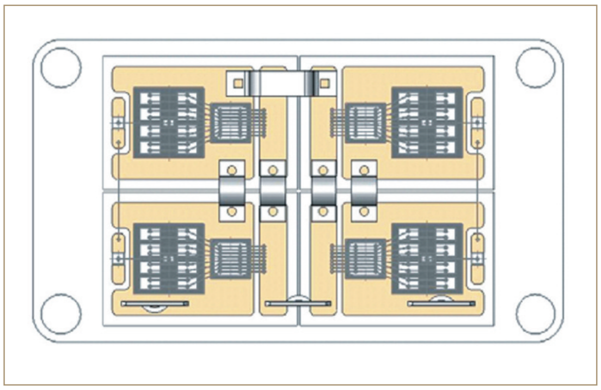


Figure 1: New module design

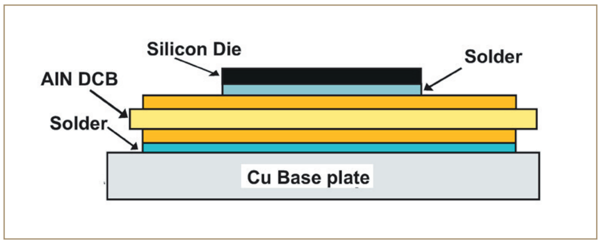


Figure 2: Structure of the soldered base module

Module design

One aim was to improve existing modules in order to increase current capability. Another requirement was to retain the high insulation level needed for the application without compromising costs and compactness. The new design was derived from an existing one and is shown in Figure 1. This new module is a full inverter leg with 1700V blocking voltage and 9500VAC insulation.

Alumina cannot be used to achieve both a high insulation voltage and low thermal resistance (R_{th}) due to the thickness required. Aluminium Nitride (AlN) was therefore opted for as it has a lower R_{th} and a higher insulation voltage than Al_2O_3.

A shortcoming of AlN, however, is the fact that it is far more expensive than alumina, meaning that costs increase. The Coefficient of Thermal Expansion (CTE) mismatch between AlN and copper is also greater than between Al_2O_3 and copper (Cu is commonly used to make base plates because of its high thermal conductivity, low cost and easy manufacture). This can lead to reliability problems. A schematic of the interface and relative CTEs can be seen in Figures 2 and 3.

The large CTE mismatch often means that expensive compounds have to be used for the plate, for example Aluminium Silicon Carbide (AlSiC), which has a similar CTE to AlN. A module with an AlSiC base plate costs up to 40% more than the same part with a Cu base plate. Although AlSiC is a must in applications where high cycling

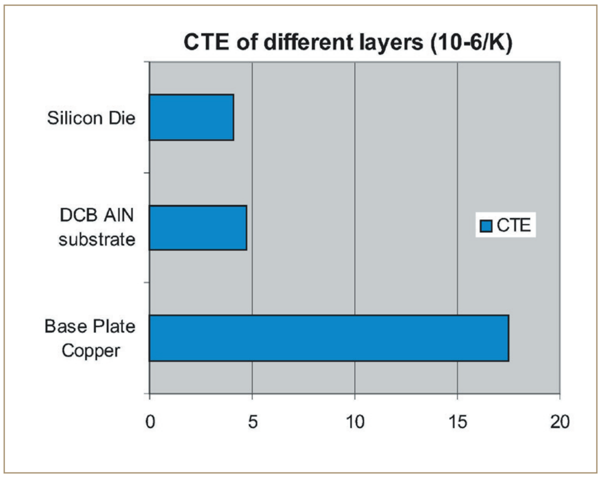


Figure 3: Coefficient of thermal expansion (CTE) of different layers

capabilities are needed (e.g. traction), it is vital that the possibility of reducing costs for less critical applications by using cheaper materials be investigated. The proposed design uses many interconnected small DCBs rather than one large ceramic substrate and a copper base plate. The use of smaller substrates keeps reliability at acceptable levels despite the difference in CTE between the materials, with cycling capability on a par with other solutions (this approach is also used for Al_2O_3-based parts for larger module sizes). The application requirement in this case (converters for auxiliary power circuitry in railways) is compliant with the relevant industrial standards.

The shear strain difference due to thermal elongation on the DCB-base plate interface is proportionate to the temperature delta and interface dimension [1], as are the stresses that occur during thermal and power cycling. Thus, reliability can be improved by decreasing the DCB length and width, provided the reliability of a smaller AlN substrate soldered on copper, even if not as good as the same substrate joined to AlSiC, meets the given application requirements. It is important to point out that DCB-base plate solder degradation is not the only failure mechanism [2] that can lead to fatigue defects: other problems arise due to terminal soldering, bonding wires, die attach and copper/AlN base plates [3,5,6,7]. These factors may cause failure to occur even sooner as a result of DCB-base plate soldering. It was found [3] that with AlSiC base plates, thermal and power cycling was poorer than expected due to problems with other module components. It therefore makes more sense to develop a well-balanced overall design rather than focusing on one area only. The importance of good soldering processes and suitable materials cannot be stressed enough; in particular, gaps in the solder should be as small as possible as they can create hot spots, raise thermal resistance and be the ultimate cause of fatigue cracks, not only on the DCB soldering.

The use of smaller DCBs can make it easier to prevent such gaps from occurring during the soldering process. Another advantage of copper over AlSiC is the improved thermal conductivity. Splitting the DCB area into a number of smaller substrates does, however, have its disadvantages, e.g. one single DCB makes better use of available space, allowing for more complex designs. Another disadvantage is the more complicated assembly process. The resultant increase in costs is evened out by the lower materials costs.

To avoid the dangerous Partial Discharge problem, a Partial Discharge Free material was used. To comply with the high current requirement, the IGBT and diode chips were replaced by newer technologies: trench IGBTs and new diodes. With the same die area, the forward voltage drop is much lower than in the former solution and the maximum junction temperature limit is higher, allowing for double the current capacity. This is partly due to the relatively slow switching frequency needed in the application, as the dynamic behaviour of trench IGBTs deteriorates as the frequency increases. To withstand the larger current, larger bonding wire was used. Software simulation was then used to uphold the theory that the rated current of the module almost doubles. The changes implemented in this new design are ready for the production line after the qualification process has been done.

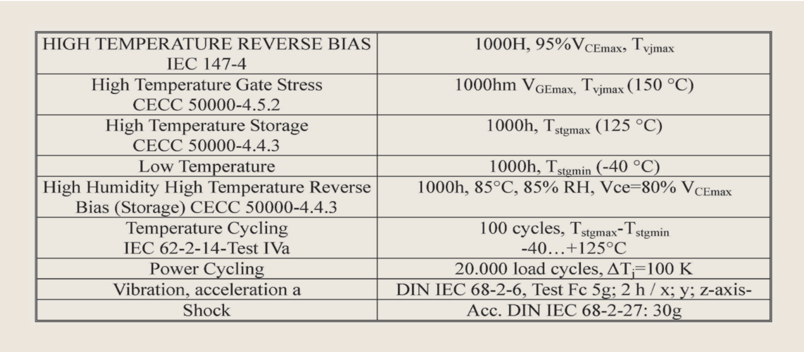
Qualification process

The qualification process involves a series of tests performed on samples (design qualification) and initial production parts (pilot lot qualification) in order to insure compliance with the features required; reliability (assessed in stress tests on the samples); and compliance with other special requirements, i.e. abnormal ambient conditions.

To consider a module suitable for production, the tests shown in Table 1 must be completed successfully. Tests are based on an accelerated stress approach, as field testing would take years to complete.

Before the tests, the static parameters, insulation, real R_{th} and mechanical properties of all parts are measured. Soldering quality is inspected using an X-ray microscope (Figure 4). All of the parameters are re-checked after the tests to see whether degradation is within the specified threshold. For power cycling, IEC 147-4 states that a minimum of 20,000 cycles must be performed with ΔT_j=100K.

Internal checks were performed using poorer parameters with at least 20,000 cycles at ΔT_j=110K. It must be noted here that in real-life applications these conditions are not present, as power modules are not used at their maximum capabilities. The Coffin-Manson or LESIT models [4] can be used to determine the expected real (service) life of the module on the basis of the test results. In our case, with a real temperature range ΔT_j=60K these models



HIGH TEMPERATURE REVERSE BIAS IEC 147-4	1000H, 95%V_{CEmax}, T_{vjmax}
High Temperature Gate Stress CECC 50000-4.5.2	1000hm $V_{GEmax,}$ T_{vjmax} (150 °C)
High Temperature Storage CECC 50000-4.4.3	1000h, T_{stgmax} (125 °C)
Low Temperature	1000h, T_{stgmin} (-40 °C)
High Humidity High Temperature Reverse Bias (Storage) CECC 50000-4.4.3	1000h, 85°C, 85% RH, Vce=80% V_{CEmax}
Temperature Cycling IEC 62-2-14-Test IVa	100 cycles, T_{stgmax}-T_{stgmin} -40…+125°C
Power Cycling	20.000 load cycles, ΔT_j=100 K
Vibration, acceleration a	DIN IEC 68-2-6, Test Fc 5g; 2 h / x; y; z-axis-
Shock	Acc. DIN IEC 68-2-27: 30g

Table 1: Reliability test for qualification

show that the module could survive for more than 400,000 cycles, which is more than acceptable for the majority of industrial applications. The module completed the qualification assessment successfully. Pilot lot approval is pending.

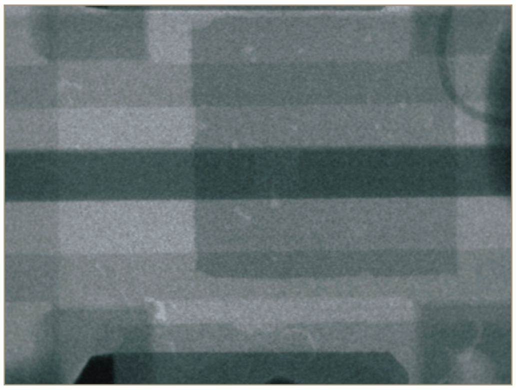


Figure 4: X-ray analysis

Conclusions

Design is always a compromise between costs and benefits: the design proposed in this article uses new technologies to improve the performance of existing parts without compromising system reliability, conflicting with the relevant industrial standards or using AlSiC as the base plate material. This material remains essential for high-demand applications, but this is not the only failure mechanism related to the base plate soldering. For this reason, this design must be carefully investigated in order to avoid other weak spots that may adversely affect the lifetime of the module parts. An overview of the qualification process was also given and describes in brief the procedures used for product approval. Finally, it is important to point out that the design and qualification processes are interdependent: the first has to be carefully studied to avoid test errors, while the second can give the designers valuable tips on how to continuously improve the products before launching them on the market.

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