A new HiPak Module Platform with Improved Reliability

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Abstract

The trend in the wide range of power electronic applications is going towards improved device reliability and quality. Especially for application using high power IGBT modules in the hundred kilowatts to lower megawatt range, like railway, T&D or STATCOM applications, the main driver of innovation moves from increase of power towards other focus topics such as quality, reliability, economics and efficiency. Large power electronic conversion systems of the mentioned applications are more-and-more used in close to 24 hours daily operation to make maximum use of the investment, thus a high up time is crucial.

To satisfy this demand, we have developed a new HiPak IGBT power module platform to improve the overall reliability performance when compared to the existing HiPak generation. The electrical behavior of this module remains unchanged, allowing for a drop-in replacement. The main process and design improvements to achieve the targeted reliability levels are presented in this paper.

1. Introduction

An improved version of the HiPak module platform has been developed to satisfy the increasing demand of higher reliability. The HiPak module range with the standard footprint is mainly used in the field of transportation, industrial drives as well as in converters for alternative energy sources such as wind-power. The reliability requirements for all these applications are continuously increasing especially with modern IGBT and diode chip-sets with higher power capabilities and increased operational temperatures. The up-time of such systems is crucial for the whole economics.

In this paper, the main technical aspects of the improved HiPak platform are described and their impact on the reliability performance is presented. First, the main packaging aspects influencing the power module reliability are discussed. Next, the technical improvements to achieve a higher reliability are detailed. In the third part, the results concerning the reliability testing are presented, followed by a short conclusion.

2. Main packaging aspects influencing the power module reliability

In addition to the semiconductor devices within a power module, the overall product reliability is mainly influenced by the process reliability (including the reliability of the connections) and the reliability of the design (including the reliability of the used materials). In this section, the main aspects out of these two fields are detailed; first for the process, then for the design.

2.1. Main process reliability aspects

One of the most challenging aspects in assembling reliable high power semiconductor devices is connecting materials with wide ranges of mechanical, thermal and electrical properties. Especially connecting materials with significantly different coefficients of thermal expansion is crucial to the product reliability and therefore demands not only innovative technologies but also well-understood and controllable processes combined with intelligent designs.

Developing processes should not only aim for better connection technologies, allowing higher lifetime capability, but should also focus towards fully controllable processes and increased process quality. This is especially valid for soldering processes, being the mainly used electrical connection. Soldered connection cannot directly be controlled during the soldering process. Therefore, the process itself has to be well controlled to achieve high process reliability. Moreover, the soldered connection must be aligned in such a way that it can be tested afterwards by means like ultrasonic-scanning or x-ray. If this is not possible, an alternative process or design need to the used.

For the new improved HiPak platform, a wire bonding process giving rise to the opportunity of in-situ process control as well as redundancy replaced the soldered auxiliary connection. For the solder main terminal connection, an in-situ process control is problematic, however superior process stability was achieved implementing design features specifically optimized for a reliable solder connection.

2.2. Main design reliability aspects

The main design aspect influencing the lifetime of a power module is the choice of materials. Here reliability aspects with respect to different environmental and operating conditions must be taken into account like high and low temperature, thermal cycling, mechanical stress, humidity, vibrations, or electrical bias, but also combinations of the mentioned conditions. Yet, the right trade-off between the most reliable materials and material properties for production, combined with the risk of material incompatibilities, is extremely difficult to achieve. For example, epoxy was widely used in power modules as a final encapsulating layer, allowing for a stable support for the terminals and minimizing the humidity penetration into the module. Today it is clear, that the epoxy does not allow for firm sealing the module, but limits the operation temperature and is critical for different aspects, like material compatibility.

In addition to the material itself, the actual design of each part has a major influence on the overall reliability. For example, an epoxy less housing needs more to focus on a mechanical robust design. Alternatively, the creepage distance of the module must not only be properly designed outside but also inside of the module. The combination of material properties, electrical functionality, influence on the lifetime and simple aspects like the spacing between the different parts within the modules require a very high understanding of both, the design functionality and the fabrication process.

3. Technical improvements

This section gives an overview of the technologies, materials and design aspects that were changed and improved to increase the overall reliability performance of the modules. First, the new housing material and design are presented. In the second section, the changes for improving the main terminal connection are explained, followed by the improved auxiliary connection. The last part shows the new emitter side bond layout.

3.1. New housing material and design

In the improved new HiPak platform, a new polyamide type housing material of glass fiber reinforced PA10 is used. This material, allows for a higher case temperature of >150°C, and is still providing sufficient mechanical stability and flexibility in the full operational range of power modules. Therefore, the material can withstand harsh environmental conditions like a combination of high temperature and high relative humidity without any significant chemical or mechanical degradation. The material is well suited for high voltage applications because of a high comparative tracking index (CTI) of 600 and a suppressed ion migration capability on the surface in a humid atmosphere. Moreover, the flammability robustness is clearly increased fulfilling new European standard EN 45545 by category R23 – HL2.

In addition to the new housing material, the module design was optimized. Because of the epoxy-less design the internal stability of each supporting part was increased. The housing and especially the case have to withstand the full mechanical stress form shocks and vibrations. To limit the repercussion of the vibrations over the main terminals to the substrates, the terminals have a stress-relief at the transition to the foot and are in contact to the cover. As a consequence, the cover has mainly to ensure the mechanical stability of the whole module and thus, the connection of the cover to the frame is quite demanding. We have therefore developed a combined snapper design. One part is designed to flexibly hold down the cover, allowing a damping of external vibrations and shocks. The other part ensures that the module is reliably closed. Other aspects regarding the designs seem less important but play a major role for the overall quality; e.g., the rounding of the edges of the frame limits the effect of mechanical impacts.

3.2. Improved main terminal design and connection

In order to increase the reliability of the solder connection between the main terminals and the substrate, the terminal design was optimized. Spacers, integrated in the terminal feet, ensure homogeneous solder layer thickness for all solder joints (see figure 1). Compared to the former design, the new terminal is only selectively coated with nickel on the bus bar connections in order to maintain the corrosion-resistant properties. On the terminal feet, a new nickel-free coating is applied resulting in improved connection between foot and solder without any micro voids in the intermetallic phase as occurred with the former nickel coated terminals. In addition, the nickel-free coating on the terminal feet guarantees controlled and optimized meniscus formation during the soldering process. Both, the implementation of the spacers and the selective coating results in higher process and product reliability.

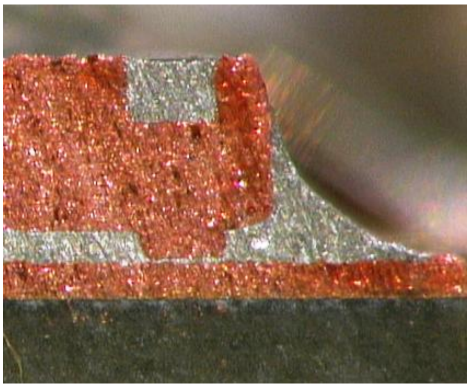


Fig. 1. Partial cross section of a terminal solder joint showing the new implemented spacers resulting in homogenous solder thickness.

3.3. New internally bonded auxiliary connection

In the existing HiPak range, the internal auxiliary connections were semi-automatically soldered followed by a visual quality control of each soldered spot. The established wire bonding technology now replaces this soldered auxiliary connection (see figure 2). As state of the art technology for the electrical connection between chips and substrate, the wedge-to-wedge thick wire bonding has successfully proven its technology trustworthiness and process stability over the last decades. Transferring the wire bonding process from the substrate to gate-print connections is unique and has specifically been developed in cooperation with one of the leading manufacturers of wire bond equipment. This process was enabled by combining a deep access bond tool with variances in bond heights of more than 10 mm.

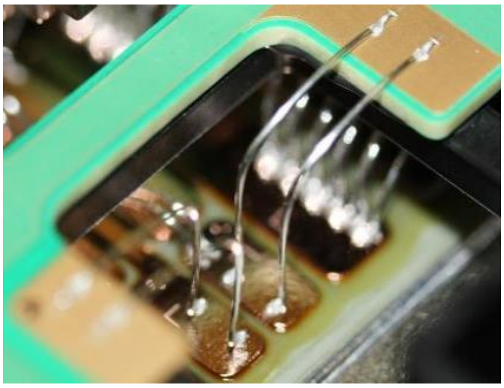


Fig. 2: New redundant bonded connection between substrate and gate-print

Compared to the former used solder process, the technology of wire bonding features several benefits. First, bonding the auxiliary connection gives rise to an automated in-line process control of each bonded connection. The automated assessment and storage of the quality critical bond parameters facilitates enhanced process quality control and monitoring. Furthermore, the wire bonding process allows an integrated non-destructive pull test of each bond site ensuring good mechanical connection between chip substrates and gate-print, thus, guaranteeing an existing electrically conductive interconnection. As a further key feature, the newly designed gate-print and the innovative process of wire bonding enable the realization of multiple wires for each connection, resulting in redundant interconnections and thus, further improved product reliability.

3.4. Improved emitter bond-layout

The cycling reliability of the emitter contact of the IGBT chips was investigated and optimized. The result is the improved emitter contact with a hybrid wire bond layout, partially applying stitch bonds. As shown in figure 3, stitch bonds are realized by bonding the wire more than once on the chip.

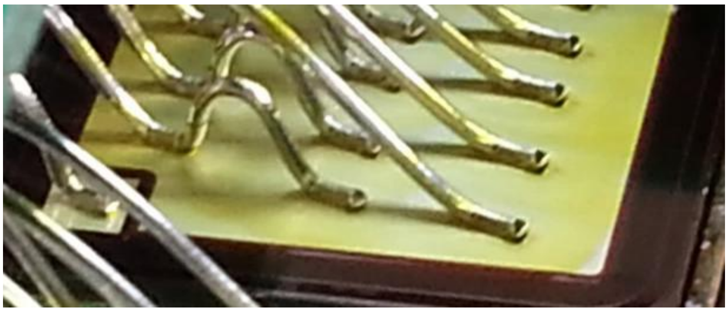


Fig. 3: New redundant bonded connection between substrate and gate-print

The improved wire bond layout has the following benefits: First, the stitch bonds provide a redundant connection to the chip. This means if one of the wire bond contacts is disconnected due to thermo-mechanical stress, the bonded wire is still electrically connected through the second contact on the chip, which definitely improves the power cycling performance. In such a case, the current commutates smoothly with increasing contact resistance to the second wire bond connection on the chip. Besides, the positive impact of the thermal capacity of a stitch-bonded wire bond presumably contributes to the power cycling performance [1].

Second, in this wire bond layout, the bond connections on the chip are decentralized. This also improves the power cycling capability, since the hottest region is in the center of the chip. This is the reason, why the stitching of the longer wire could be a disadvantage for the power cycling capability, if not combined with other means.

Finally yet importantly, this wire bond layout provides a higher uniformity of the current density distribution throughout the chip metallization [1]. According to FEM simulations (COMSOL Multiphysics), more than 30% of the total current on a stitched bond wire flows on the stitch-bridge between the two bonds. The simulation results also showed that the local high current density peaks on the chip are suppressed and a uniform current distribution on the chip is achieved.

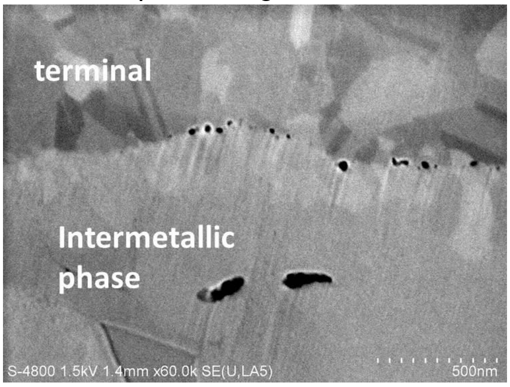
4. Results

All standard qualification tests (temperature cycling, temperature humidity bias, etc.) were performed with the improved HiPak module, showing that all reliability expectations could be met. In this section, the results of the main qualification tests are presented.

4.1. Higher process reliability

As described in section 3, several processes were optimized. Regarding overall product reliability, the two most substantial processes are the improved main terminal soldering and the adopted auxiliary wire bonding.

For the soldering process, the adaptations result in increased stability of the soldered connection preventing the formation of voids at the terminal foot interface as shown in figure 4.



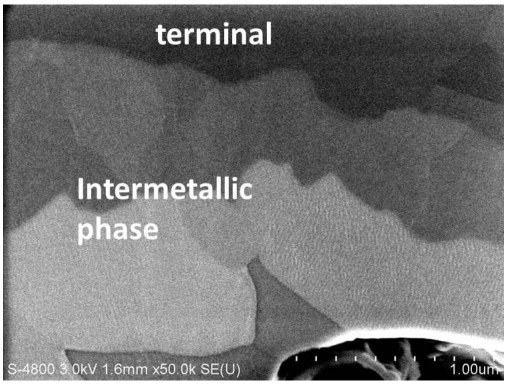


Fig. 4a.) SEM images of the former terminal solder joint showing void formation between the terminal-solder interface in the nanometer scale

b.) SEM images of improved main terminal solder joint showing homogenous void-free terminal-solder interface.

Furthermore, the reproducibility of the solder thickness between substrate and terminal is facilitated. Both, nickel free terminal foot coating and spacers, result in improved wetting behavior of the solder and therefore beneficial meniscus formation during the solder process. In addition, these technical improvements also increase the degree of freedom of the soldering process by reducing the sensitivity against process fluctuation.

The in-line pull tester for the wire bonded connection between substrate and gate print enables an automated 100% control of each bonded connection. In addition to the independent redundancy, this in-line control significantly increases the process reliability and thus improves the overall product reliability. All critical to bonding quality parameters such as deformation, induced ultrasonic power and pull-test results are recorded and stored for each single bond connection facilitating real-time quality monitoring as well as long term quality tracking.

4.2. Higher operation temperature range

Do to the new design without epoxy and the new housing material, the operation temperature range of the modules could be increased to 150°C. For test purposes only, the modules were stressed for 24 hours at 175°C. The mechanical properties remained unchanged. The modules were still fully functional, only showing slight deviations in the electrical parameters regarding the leakage current. This temperature is yet not to be applied for longer duration and is not guaranteed. It only shows that the new module platform is actually not the limiting factor for the high temperature operation.

4.3. Better humidity behavior

No chemical or mechanical degradation of the housing material occurs when exposing power modules to atmospherically conditions of high temperature and high humidity as it was done in the temperature-humidity-bias (THB) test. Moreover, the module behaved in the desired way, not storing the humidity within the module and showing no sign of degradation of the used materials. As required for the qualification, the electrical functionality was not affected by the test

Furthermore, the behavior of the material with respect to humid atmosphere according to possible customer applications was proven by an ion migration test on material samples and by exposure of assembled modules to salt mist (according to DIN EN ISO 9227, NSS). In the ion migration test a voltage of 4.35 kV was applied to the material samples in an atmosphere of 85°C and 85% relative humidity for 168 hours. After that, the samples were investigated by SEM/EDX for possible agglomerations of critical ions like Cl-, Br-, P-, F-, Ca++ in the vicinity of the electrode positions for electrical contacting of the samples. On all samples of the PA10 material, no significant agglomerations of the corresponding ions could be observed.

In the salt mist test, two modules were exposed to a salt mist with a concentration of 5% NaCl at a temperature of 35°C for 96 hours. In the visual inspection of the modules after the exposure to the salt mist, no contaminations were found on the surface of module housing, that were directly related to the housing material or to any chemical reaction of the housing material with other substances. After cleaning the modules, the modules passed all electrical tests.

4.4. Higher power cycling capability

The power cycling performance of the emitter contact of the improved HiPak modules was investigated in two different power cycling experiments. The focus of these experiments was applying thermo-mechanical stress to the improved wire bond layout. Thus, the cycling conditions of a cycling period of 0.7 s with a 50% duty cycle were set in order to achieve the respective junction temperature swings of (a) T_j: 90 °C – 150 °C and (b) 100 °C - 170 °C. The improvement in the power cycling capability is shown in figure 5.

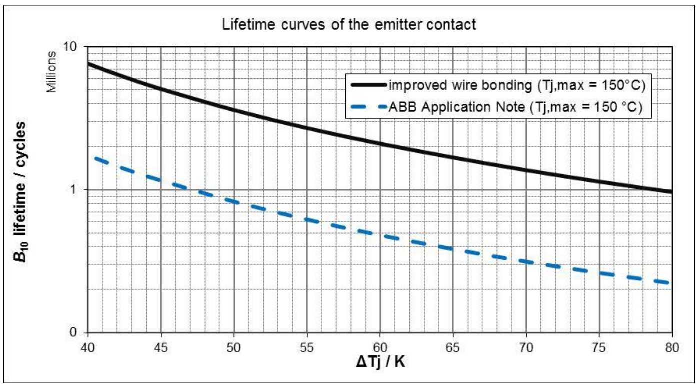


Fig. 5: The 10% power cycling capability curves (Tj,max=150°C) of the improved emitter contact and the previous emitter contact (given in the ABB application note [2])

Both of the experiments (Tj,max = 150 °C and 170°C) resulted in a four times higher power cycling capability of the improved emitter contact of the new HiPak module platform. The resultant power cycling capability is given as a B10-lifetime curve in figure 5 and is above the reference lifetime curve indicating an improved power cycling performance. The reference lifetime curve in figure 5 can be found in the ABB application note "Load-cycling capability of HiPak IGBT modules" [2].

5. Conclusion

The new HiPak platform combines reliability improvements with the advantage of maintaining the overall electrical and thermal behavior of the module. This allows for a direct replacement of the modules by the system user while benefiting from the improved reliability performance for enabling higher power and higher operational temperatures. The increased reliability was achieved by improving the existing designs and processes, combined with the introduction of new materials and processes where needed.

6. References

[1] J. Lutz, H. Schlangenotto, U. Scheuermann and R. De Doncker: "Semiconductor Power Devices – Physics, Characteristics, Reliability", Chp.11, ISBN: 978-3-642-11124-2 (2011).

[2] ABB Application note: "Load-cycling capability of HiPak IGBT modules"; 5SYA 2043-03 (2012)