Hybrid circuit board structure for power electronics

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Keywords

«Gallium Nitride (GaN)», «Half-bridge», «Hybrid», «Wide bandgap devices», «Thermal design»

Abstract

The objective of this paper is to show a novel approach for integrating GaN semiconductors as a discrete SMD component using an additional printed circuit board (PCB) for the power electronics of a PV inverter. This additional PCB is designed as an integrated metal substrate (IMS) circuit board to conduct the dissipated heat from the semiconductor into the heat sink. The IMS board is soldered with a BGA connection to a larger mother board. Therefore, usual production steps of electronics production are used to make the structure as simple as possible.

Introduction

Current power electronics in PV inverters largely use discrete (through-hole technology / THT or surface-mount technology / SMT) semiconductor packages or so-called power modules with solder or press-fit pins. The use of power modules allows a higher circuit complexity per area and better cooling. Thereby, the conventional power modules have quite high parasitic inductances, due to the construction technology with pins, leads and bond wires. Those parasitic inductances have a negative effect on the electrical performance of fast switching power electronics with wide band gap (WBG) semiconductors such as voltage overshoot [1]. Semiconductors for the surface-mounting technology (SMT) manufacturing process packaged as surface mount device (SMD) have smaller parasitic inductances [2]. Many GaN semiconductors are available in a SMD package. If such discrete packages are used, the PCB design is essential for electrical and thermal performance.
In this paper a novel hybrid construction approach with IMS boards will be presented to integrate GaN semiconductors as a SMD package on a larger power electronics assembly. Ball Grid Arrays (BGA) are used to connect the IMS board with a larger FR4 motherboard. GaN semiconductors on IMS boards have already shown their potential [4]. With the presented approach it is possible to integrate GaN semiconductors into PV and storage inverters to benefit on system level.

The boundary conditions for the chosen assembly are to maintain electrical insulation of the electronics to the heatsink. The power electronic should bridge the gap between the motherboard and the heatsink to maintain a simple heatsink design with a flat surface without a pedestal. As thermal interface material a thermal grease shall be used. Therefore, a construction approach with a castellated board or a PCB with thermal vias (like they are proposed in application notes) together with an insulating foil as thermal interface material could not be used.

Insulated metal substrate boards

The simplest structure of an IMS circuit board consists of a metal substrate, an insulating prepreg layer and the copper layer with the desired layout. IMS circuit boards are available with a copper or aluminum substrate. The thickness of the available substrate can vary. Standard thicknesses of 1.0, 1.5 or 2.0 mm are available or can be ordered on request. Usual thicknesses for the insulating layer are 50 to 100 µm. Typical values for the thermal conductivity of such prepregs are 3 to 4 W/(m·K) but values up to 12 W/(m·K) are available, too [5], [6]. The typical thermal conductivity of standard FR4 is between 0.3 to 0.4 W/(m·K). In comparison thermal enhanced prepregs for IMS boards have roughly 10 times better thermal conductivity than standard FR4 material. Multilayer IMS boards with more than one layer and up to six layers are also available. Fig. 1 shows a schematic cross section of a two-layer IMS PCB. The two layers can be connected with microvias. Those vias can be designed as blind vias or as copper filled vias. Copper filled vias can be used to improve the thermal conductivity of the FR4 core between the two copper layers. However, the aspect ratio, the ration between drill diameter and hole depth, of the PCB manufacturer must always be taken into account.

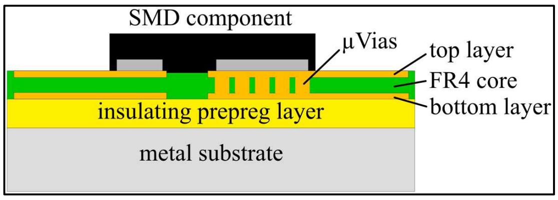

Fig. 1: Schematic cross section of a two-layer IMS board

Construction of a demo board

The structure of the power electronics demo board consists of two circuit boards. The IMS circuit board with the power switches and a motherboard which, in addition to the IMS circuit boards, is holding other components like DC link capacitors, filter components, galvanic isolated driver supply, digital isolator and additional circuits for evaluation.

The connection between the IMS board and the motherboard is realized through a so-called Ball Grid Array. Normally BGAs are used to connect packages with integrated circuits with a variety of solder joints with a PCB. In this approach the BGAs are used to connect the half bridge with the DC+, DC-, bridge-out potential and the driver IOs from the driver integrated power switch to the motherboard. Fig. 2 shows a schematic cross-section of the IMS connected to the motherboard by BGAs. Because of the dimensions of the components mounted on top of the IMS it is necessary to add a milling into the motherboard. Through this milling the components are visible, and it is possible to evaluate the semiconductors with a thermal camera. The IMS is soldered on the bottom side of the motherboard. This board is screwed to a heatsink.

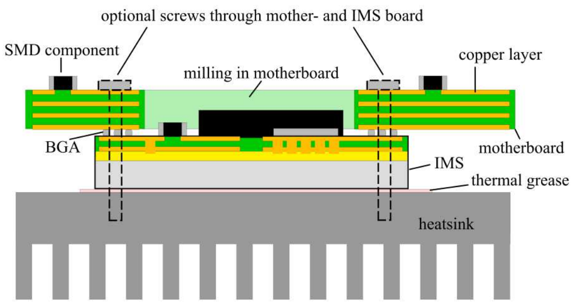

Fig. 2: Schematic cross-section of a hybrid PCB-IMS construction with SMD components and the BGA solder joints between the motherboard and IMS board

The circuit on the IMS board contains a half bridge with samples of the LMG3422R050 from Texas Instruments. This device includes a 600V GaN chip with an integrated driver, temperature reporting and protection features [7]. For the driver to function properly it is necessary to place some components close to the device on the IMS. Therefore, the IMS board can be divided into a power part and a driver part with the additional components and solder joints. Fig. 3 shows the designed IMS board.

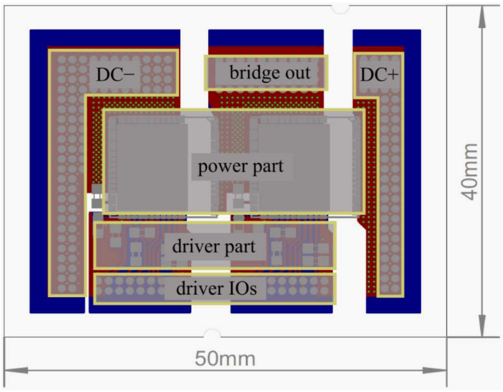

Fig. 3: Designed IMS board with marked areas for the BGA solder joints and components

The designed IMS board is 40 mm by 50 mm and features 224 solder pads for the BGA solder joints. In the datasheet of the LMG3422R050 a four-layer stack-up is recommended but for a better thermal performance a two-layer design with copper filled microvias was chosen. Most of the vias are placed under the exposed thermal pad of the semiconductor to create a better thermal conductivity from layer one to layer two. With this design approach, it was not possible to place a DC link capacitor between 'DC+' and 'DC-' directly onto the IMS and minimizing the influence of the DC link inductance. Instead, the DC link capacitor was placed onto the motherboard. As metal substrate 1.0 mm thick copper was used. The insulating prepreg layer has a thermal conductivity of 3 W/(m·K) and is about 100µm thick. In the driver section of the IMS board the vias are placed to connect the ground pins with a ground plane from the driver part.

The production process was carried out with the typical steps of an electronics manufacturing and consists of the following steps:

1. IMS board is squeegeed with solder paste in a stencil printer with a stencil
2. Components are placed on IMS board by a pick-and-place machine
3. Soldering through a reflow oven of the IMS
4. IMS boards are placed inside a tray or reel for the pick-and-place machine
5. Bottom side of the motherboard is squeegeed with solder paste
6. Components and IMS board(s) are placed on bottom side of the motherboard
7. Soldering through a reflow oven of the motherboard
8. If needed, repeat last three steps for top side of motherboard

X-Ray Analysis

After the production process had been completed, the construction of an IMS board soldered onto a motherboard was examined using an x-ray device. Fig. 4 shows the top view of the soldered PCBs and the soldered balls are visible as darker circles. The balls have a much higher contrast in comparison to the copper layer around. That is an indication of a correct connected solder joint between the two circuit boards.

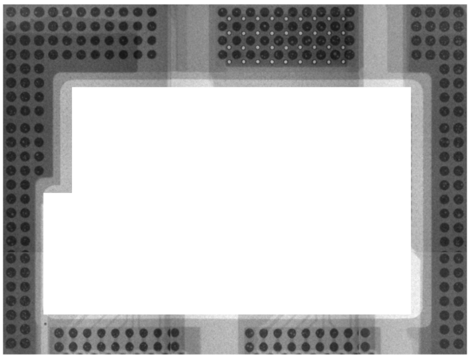

Fig. 4: X-Ray of IMS board soldered to the motherboard

In comparison Fig. 5 shows an x-ray of a test run in which only one circuit board was prepared with solder paste. Therefore, there is less solder paste available to connect the two pads and form a correct solder joint. The solder pads with higher contrast are outlined in green and the solder pads with less contrast is outlined in red. It is visible that the ball pads in the red marker have less contrast in comparison to the others. This is an indication that the pads of the motherboard and the IMS board have no contact to each other. The assumption is as follows: When enough solder paste has been applied to bridge the gap between the two pads, the ball forms like a pillar between them. If there is not enough solder paste, it forms some sort of hill due to the surface tension on the pad. In an x-ray image thicker material or materials with higher density appear darker. Fig. 6 illustrates this assumption.

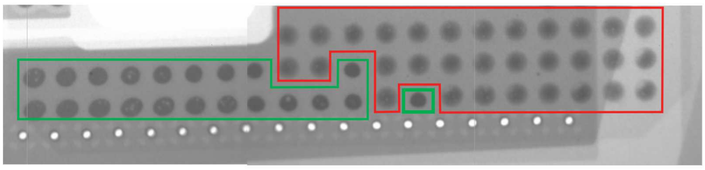

Fig. 5: X-ray of a BGA solder joint connection between a standard PCB and an IMS board; Green: BGA with high contrast; Red: BGA with less contrast

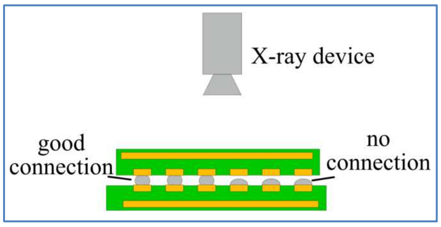

Fig. 6: Schematic x-ray of a BGA with good connections and no connection between two PCBs

This assumption could be checked with a continuity test on some driver IO connections in the test run with less solder paste. Some of those connections appeared darker and a visible difference in contrast was evident and only two balls are connected in parallel. The continuity test with a multimeter confirmed the assumption.

In Fig. 4 some balls show little bright spots. These spots are an indication of solder voids. Various effects concerning the lifetime and reliability of BGA solder joints were already investigated in [8] and [9]. Further investigations similar to [3] must show if those voids can lead to a failure of the soldered balls in combination with the heat coming from the power semiconductors and the presence of the contact pressure from the screw connection to the heatsink.

Thermal Performance

The thermal performance was investigated by determining the thermal resistance between the device junction and the heatsink base. A reverse DC current through the device was applied. The current and the voltage across the device were measured with a Yokogawa Power Analyzer. The temperature was measured with the infrared camera FLIR T365. A thermo couple was placed at a blind hole in the heatsink base underneath the device to measure the heatsink temperature underneath but as close as possible to the bottom side of the IMS.

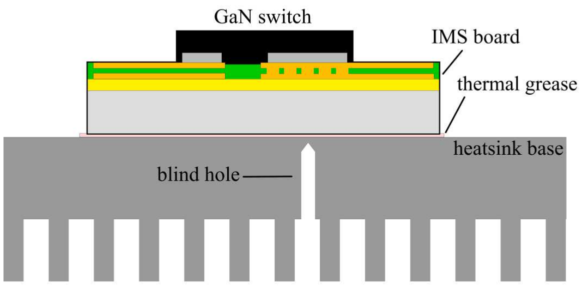

Fig. 7: Schematic cross-section of the test setup for determining the temperatures with a blind hole in the heatsink base

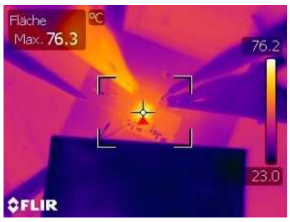

Fig. 8: Thermal image of the DUT with an applied Power P_{loss} of 20,0W

The thermal impedance $\mathrm{R_{th,j-h}}$ can be calculated with the measured temperature values:

$$R_{th,j-h} = \frac{T_{Junction} - T_{Heatsink\ base}}{P_{loss}} = \frac{76{,}3°\mathrm{C} - 34{,}4°\mathrm{C}}{20{,}0\mathrm{W}} = 2{,}095\ \frac{\mathrm{K}}{\mathrm{W}} \quad (1)$$

The thermal impedance $\mathrm{R_{th,j-h}}$ is around 2,1 K/W even though the x-ray image showed a larger number of voids in the solder joint of the device to the IMS board.

Switching Performance

Switching performance had been evaluated with an oscilloscope with 1 GHz bandwidth and 20 GS/s and differential probes with a bandwidth of 400 MHz. With the proposed converter the maximum achieved switching speed was 40 V/ns with a DC link voltage of 400V. The efficiency in buck converter mode was around 98% at a power level of 2 kW. However, the max. voltage peak during switching transition was 738V resulting in an overvoltage of 338V and significant ringing.

From these results it can be concluded that the DC link inductance in the layout is too high. It seems to be necessary to arrange the switches in side by side with additional ceramic capacitor to achieve a significant lower commutation loop.

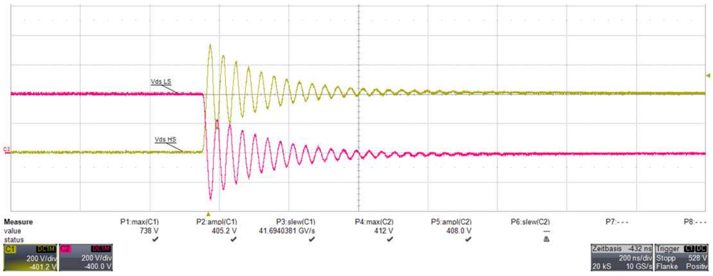

Fig. 9: Switching waveforms of the high-side turn-off switching transition

Conclusion

This paper presents the design of a power electronics stage with a hybrid PCB construction. The construction is based on a copper based IMS board and the surface mount technology (SMT) production process in a typical electronics manufacturing. BGAs were successfully used to connect the two boards. Based on x-ray pictures, the solder joint connection between a standard PCB and an IMS board were investigated and except for a number of small voids in the solder joint no failure due to production process were detectable. First tests of the IMS board were successfully performed with an inverter motherboard.

References

[1] A. Anthon, J. C. Hernandez, Z. Zhang and M. A. E. Andersen, "Switching investigations on a SiC MOSFET in a TO-247 package," IECON 2014 - 40th Annual Conference of the IEEE Industrial Electronics Society, 2014, pp. 1854-1860

[2] A. Lemmon, S. Banerjee, K. Matocha and L. Gant, "Analysis of Packaging Impedance on Performance of SiC MOSFETs," PCIM Europe 2016; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management, 2016, pp. 1-8.

[3] C. Schwabe, N. Thönelt, T. Basler, "Reliability investigation of SiC MOSFETs under switching operation in various packages," CIPS 2022 - 12th International Conference on Integrated Power Electronics Systems, 2022

[4] J. L. Lu, D. Chen, L. Yushyna, "A high power-density and high efficiency insulated metal substrate based GaN HEMT power module," 2017 IEEE Energy Conversion Congress and Exposition (ECCE), 2017, pp. 3654-3658

[5] LeitOn, Design Rules for Aluminum IMS, online available:https://www.leiton.de/technology-alu-printed-circuits.html

[6] LeitOn, Design Rules for Copper IMS, online available: https://www.leiton.de/technology-copper-printed-circuits.html

[7] Texas Instruments, Datasheet, LMG342xR050 600-V 50-mΩ GaN FET with Integrated Driver, Protection, and Temperature Reporting datasheet (Rev. A), online available: https://www.ti.com/product/LMG3422R050

[8] Qiang Yu, T. Shibutani, Y. Kobayashi and M. Shiratori, "The Effect of Voids on Thermal Reliability of BGA Lead Free Solder Joint and Reliability Detecting Standard," Thermal and Thermomechanical Proceedings 10th Intersociety Conference on Phenomena in Electronics Systems, 2006. ITHERM 2006., 2006, pp. 1024-1030, doi: 10.1109/ITHERM.2006.1645457.

[9] R. Yano and Q. Yu, "The life cycle impact assessment that the variabilities of BGA solder connection makes," 2017 IEEE 19th Electronics Packaging Technology Conference (EPTC), 2017, pp. 1-6, doi: 10.1109/EPTC.2017.8277488.