

A novel manufacturing technique for integrating magnetic components windings on power module substrates

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Keywords

«Packaging», «Passive component integration», «Thermal design», «Intelligent Power Module (IPM)», «Passive components»

Abstract

In this paper a novel manufacturing technique is investigated with the aim of integrating magnetic components (e.g. inductors and transformer) on power module substrates together with the switching devices, to minimize overall dimensions and improve thermal management. The proposed approach consists of bonding copper U-shapes, representative of individual turn of the windings, onto the substrate. This offers an enhanced thermal exchange between the inductors and the cooling system and hence an increase in the current density.

Introduction

The introduction of wide bandgap (WBG) semiconductor devices has led to the possibility of increasing the switching speed and the operating temperature. However, due to the related challenges, these potential benefits have not been fully exploited yet. The current strategy for creating high power converters consists of connecting individual semiconductor devices in parallel within the power module to meet the required current rating. This inevitably results in an increase in the physical size of the substrate used to accommodate the dies. This in turn will increase the parasitic inductances within the power module. In addition to that, because of physical differences in the current paths and proximity effects, dynamically the transistors will not share the load current uniformly. The catastrophic result of these two phenomena is that the switching speed needs to be reduced much below the actual capabilities of the WBG devices. Indeed, in order to increase the switching frequency, the requirements of minimising the parasitic elements and containing the electromagnetic interference became stringent. In [1], [2] the authors proposed a modular approach, based on single basic power cells, intelligent power modules that integrate filters and gate drivers circuit. This approach allows to optimise locally the commutation loop and the gate driver circuit, hence reducing the parasitic inductances to reach SiC and Gan full potential. In addition to that, the physical integration of the output inductor together with the switching devices on the same substrate can give further benefits [3]. Firstly, thanks to this packaging solution the high frequency switching noises are contained at the source and do not contaminate the end user. Secondly, if the inductor windings are directly bonded onto the substrate, a better thermal path can be achieved

enabling higher current densities. However, the actual implementation of this concept through a cost effective and consistent route poses a serious challenge.

Switching at very high frequency (e.g. 1-5 MHz) causes higher copper losses in magnetic components due to skin and proximity effect. One of the traditional ways to attenuate these phenomena is by using Litz wires [4],[5]. However, this approach results in a dramatic increase in costs, and the inferior thermal conductivity of Litz wires compared to solid wires may reduce the positive effect gained by lower losses. Another interesting approach to minimize the AC losses is to use a combination of thin and thick foil windings connected in parallel together with a quasi-distributed gapped core [6]. Compared to Litz wires, this approach is reasonably cost effective, it leads to a better exploitation of the core window and finally it is much easier to find fine copper or aluminium foils (e.g. for application beyond 1 MHz) than fine stranded Litz wires. Despite of its many advantages, because of termination and winding issues, there are no industrial processes that offer to implement this technique in an automated way that could be compatible with power module manufacturing. In this terms, considering also the increasing interest in PCB/DBC hybrid power module [7] [8], through silicon vias (TSV) [9] and polymer embedded vias (PEV) [10] are certainly an excellent option. Indeed, they employ well established processes and go in the direction of having a compact passive component integrated onto the substrate. However, due to coefficient of thermal expansion (CTE) mismatch between silicon/polymer and copper, these approaches cannot be used to manufacture vertical connection longer than few millimeters. This poses a practical limit in the maximum effective volume where the magnetic energy can be stored, resulting in a serious challenge to produce power inductors. Finally, a manufacturing route for integrated inductors winding that has been already adopted is bond wire magnetics. In this case, the turns are made of single or multiple bond wires, which enables inductance tuning through loop dimension and AC resistance control by selecting the appropriate size of the single wire. Even though this process is compatible with power module manufacturing, due to the low current capability of the wire bond, so far, the applications of this method have been micro-transformers and micro-inductors for integrated circuit (IC) [11] [12].

In [1] and [2] the inductors are machined from a Cu bulk to create the desired winding shape, and one side is bonded on a direct bonded copper (DBC) substrate so that the inductors and the power switching cells are cooled using a shared cooling system. Thanks to this enhanced thermal path and a jet impingement cooling concept it is possible to achieve high current density (e.g. 50 A/mm²) without excessive thermal stress [13]. The drawbacks of this approach are mainly related to the manufacturing process of the copper windings, which turned out to be expensive and not consistent. In this paper a novel manufacturing method is proposed. Instead of using a single bulk winding component, multiple copper U-shaped parts are proposed for creating the inductor and are directly bonded on a patterned DBC enabling a high thermal exchange with the substrate. The investigation is focused on finding the most efficient technique of bonding the Cu U-shapes to obtain a good bonding strength, which is related to reliability and thermal behaviour. The possibility of automating the procedure using widely used facilities in power module

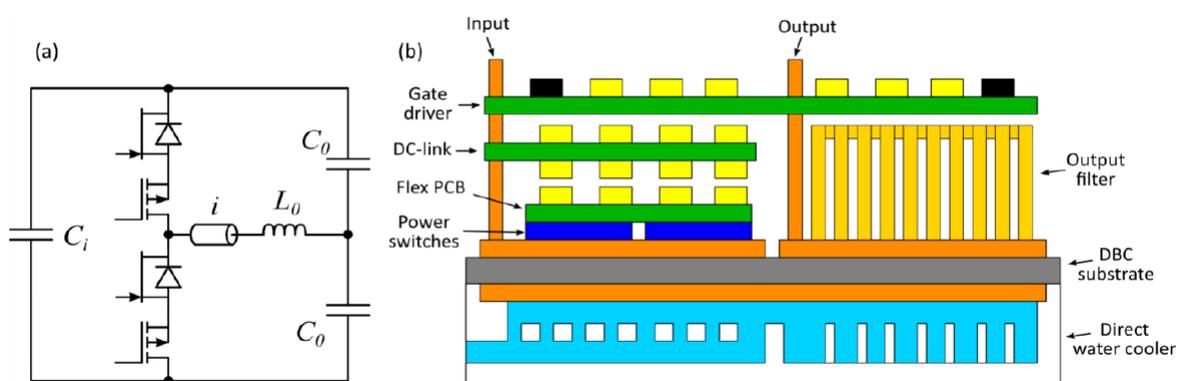


Fig. 1: (a) Single Basic Power Cell (SBPC) circuit and (b) a cross sectional schematic of the SBPC design placed on direct water cooling system

manufacturing has been taken into account. Three techniques are investigated: soldering, pressure-assisted and pressure-less silver sintering. Shear tests and optical analysis of the bonding area used to evaluate the bonding strength of Cu U-shapes are also included. Finally, a full inductor has been built as concept demonstrator, and its electrical performance have been analysed through small signal analysis and compared to Finite Element Analysis (FEA) simulations.

Inductor integration on power module substrate

The Standard Basic Power Cell (SBPC) proved that the concept of using a modular approach results in a significant increase in the switching frequency. In order to minimize the commutation loop inductance, instead of connecting multiple dies in parallel within the power module, the solution is to connect more basic commutation cells in parallel. As a result, the commutation inductance can be optimised locally and the switching behaviour of the devices will not be compromised. In this way, the gate drivers circuit can be located as close as possible to the dies minimizing the chance of coupling noises that could cause false turn-on. Each SBPC also includes all the passive components needed for filtering and for its own independent operation, resulting in no conducted propagation of harmonics and EMI. In addition to that, an output inductor is needed for each commutation cell to be able to use them in parallel. Fig.1 illustrates the SBPC and its corresponding circuit, showing the power switches and the inductors bonded on a single DBC substrate.

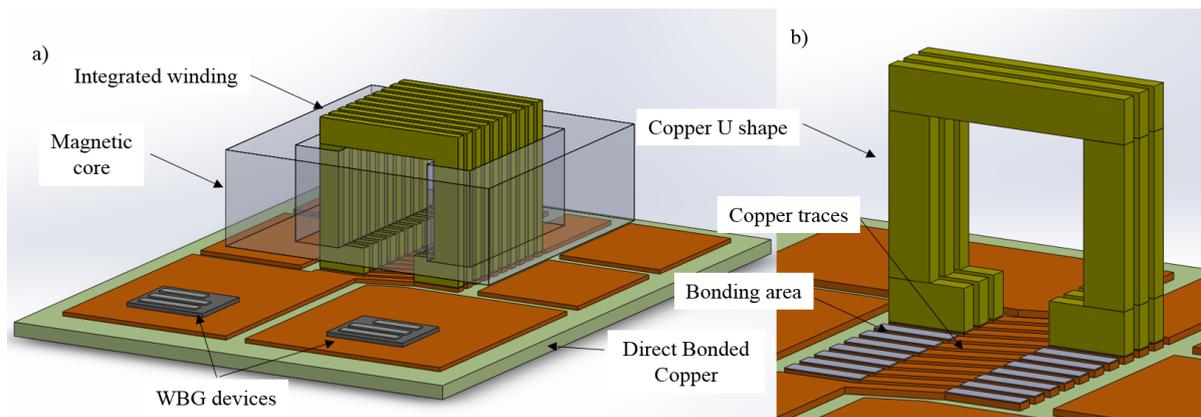


Fig. 2: a) Integrated version of Single Basic Power Cell (SBPC) (b) proposed U shape structure for winding manufacturing

In the integrated version of SBPC, the output inductor and the power switches are bonded on the same Aluminium Nitride (AlN) DBC substrate, as shown in Fig. 2.a. A part from EMI containment, this arrangement is also beneficial for the thermal aspect. In conventional inductors, only the input and output terminal are electrically and hence thermally connected to the substrate, thus resulting in a non-uniform temperature distribution. In particular, there is a peak temperature in the central turns, whereas when all the turns are directly bonded to the DBC, the temperature is constant across all the turns. To achieve this structure, the proposed solution is to use individual copper U-shapes bonded on copper traces to create the electrical conduction path.

A comparison based on magnetic and thermal co-simulation using Finite Element Analysis (FEA) has been carried out and the results are illustrated in Fig 3. In the first case (Fig.3.a), a solid solenoid (one bulk) is used and only the first and the last turns are bonded to the copper traces of the DBC, whereas the rest of the inductor is laid on the substrate. In the second case (Fig.3.b), individual U-shapes are bonded onto the substrate. The geometry and boundary conditions are the same in both cases, a static current density of 50 A/mm^2 is applied and the bottom of the DBC is kept at room temperature. Soldering has been considered as a bonding technique (contact thermal conductance: $3 \times 10^6 \text{ W/m}^2 \cdot ^\circ\text{C}$), whereas regarding the non-connected turns nylon has been considered as wire insulation (contact thermal conductance: $500 \text{ W/m}^2 \cdot ^\circ\text{C}$).

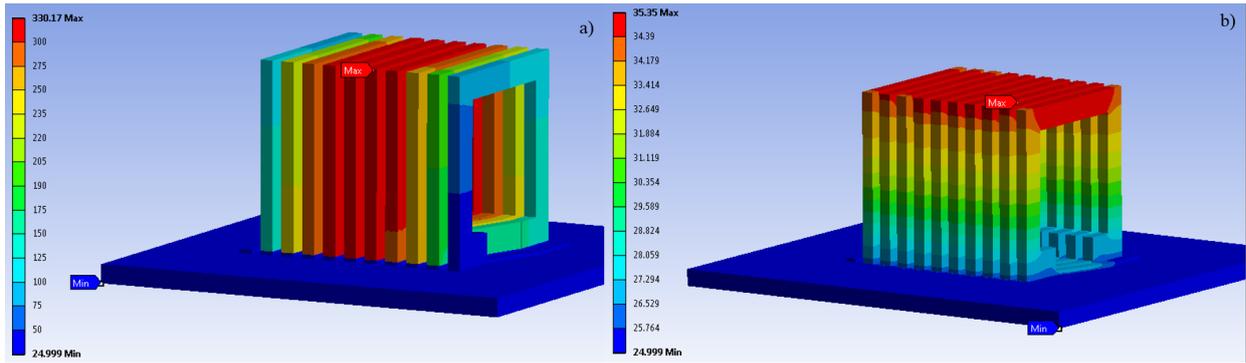


Fig. 3: Temperature distribution [°C] : a) in a solid copper solenoid bonded at the terminals only , b) in a U-shapes winding inductor soldered on DBC

Experimental Procedures

U-shapes manufacturing

Many possible manufacturing processes have been considered to manufacture the Cu U-shapes to build the inductor (e.g. stamping press, wire forming, electron-beam machining). Finally, laser cutting has been chosen because it offers a cost effective route without sacrificing the dimensional accuracy. A large copper sheet with the corresponding thickness was employed and U-shapes were cut out with the laser (Fig. 4a). In order to achieve good bonding, the copper has been coated using Electroless Nickel Immersion Gold (ENIG) to prevent oxidation and to ensure a good sintering (Fig. 4b). The substrates used for this set of experiments are AlN based DBC with gold finished surface.

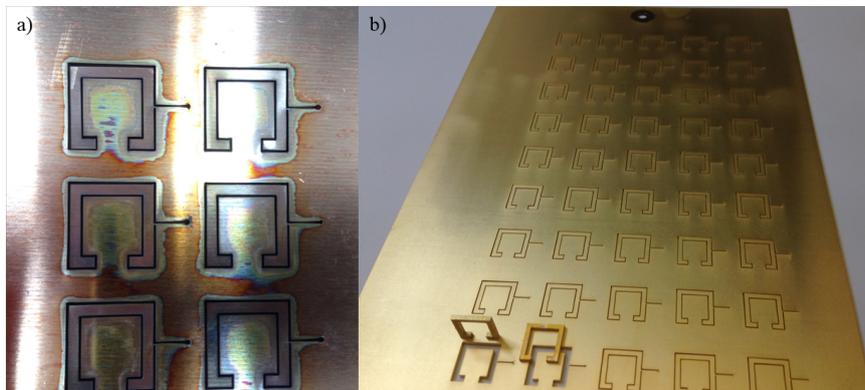


Fig. 4: Copper U shapes, a) after laser cutting b) after ENIG coating

Pressure-assisted Ag sintering

The pressure-assisted sintering has been performed using nano-powder silver (Ag) paste. To develop an automated process, the Datacon 2200 evoplus die bonder is used for both placing and sintering. This ensures that the inductor integration can be performed as a part of the power module assembly. The first step consists of screen printing the Ag paste on the bonding area by using a 100 μm thick stainless steel stencil to form two pads for the U-shape feet. An appropriate tool for the bonding head has been designed to allow the machine to pick and place these particular pieces. Following the parameters optimisation performed in [14] and [15] a type of nano-silver paste which can be pre-dried to burn out organic ingredients before die placement, was used. The drying step is performed at 130°C. After placing the U-shapes, a pressure of 10 MPa is applied by the bonding head, and heat is transferred both from the bonding head and the substrate by keeping them at 300°C while the sintering occurs. When multiple turns are needed, sequential sintering can be performed by dispensing the paste or through film transfer. Sintering time has been varied to relate the bonding quality to process duration.

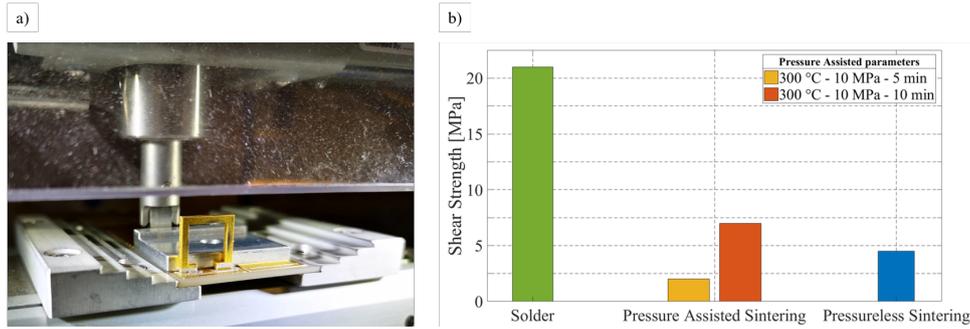


Fig. 5: Shear test: a) test layout, b) results

Pressure-less Ag sintering

This variant of Ag silver sintering has the advantages of being performed on non-coated surfaces and since there is no need for pressure, the manufacturing process can be simplified increasing the productivity. For the pressure-less sintering process, the screen printing and the U-shape placing steps are the same of the pressure-assisted sintering. On the other hand, in this case the sintering is performed in a reflow oven, after the Cu pieces are placed on the bonding area. The temperature profile includes a drying step at 100°C to remove the organics and a sintering temperature of 260°C which is hold for 60min. The whole process is performed under nitrogen atmosphere.

Soldering technology

The third bonding technique that has been investigated is solder technology. The solder alloy (63Sn-37Pb) is screen-printed on the DBC and the Cu U-shapes are placed on the bonding areas using a ceramic jig for alignment purposes. The sample is then placed in an oven at 210°C, for 10 minutes for the solder reflow.

Results and discussion

The different bonding techniques have been evaluated through shear test using DAGE 4000 plus shear tester. The results and the test setup are shown in Fig. 5. The solder joint is seen to have an excellent shear strength, equal to 21 MPa. The pressure-assisted sintering process outcome has been proved to be highly sensitive to the sintering time. A shear strength of 2 MPa and 7 MPa was obtained for 5 and 10 minutes of sintering time respectively. The shear strength of the pressure-less sintering joint is comparable with the pressure-assisted sample, but they are both weaker compared to solder technology. The low mechanical strength of the sintered joints can be attributed to the surface finishing of the U-shapes. Due to laser cutting process, the Cu U-shapes present a rough bonding surface. The roughness of the pieces has been measured using Zeta-20 Optical Profiler, an image of the piece bonding area and its surface profile are shown in Fig. 6 for two different thicknesses of copper: 0.7 mm and 1.5 mm. The arithmetical mean surface roughness is respectively 7.9 μm and 8.6 μm . While shear strength at first increases with surface roughness because of increased contact area and mechanical interlock [16], when the surface is too rough, the sinter paste is not everywhere in contact with the bonding areas, this inhibits the diffusion mechanism and the joint presents large voids and non-sintered areas, see Fig. 7.a and Fig. 7.b. Polishing the copper pieces prior ENIG coating could be an option to improve the sintering process, however this will add a manual operation that would compromise the cost effectiveness of the whole manufacturing route. On the contrary, reflowed solder can flow and spread itself below the rough surfaces, resulting in a good bond see Fig. 7.c.

Taking into account the results of mechanical tests, a full inductor has been manufactured using solder technology. The result is a 10 turns air-cored inductor directly integrated on a AlN based DBC. The turns spacing is 300 μm and the copper thickness is 700 μm , with a copper cross-section of 1mm² the footprint is a 10x10mm, more geometric details are indicated in Fig. 8a. This sample proves the feasibility and the consistency of the proposed manufacturing route for magnetic integrated power modules.

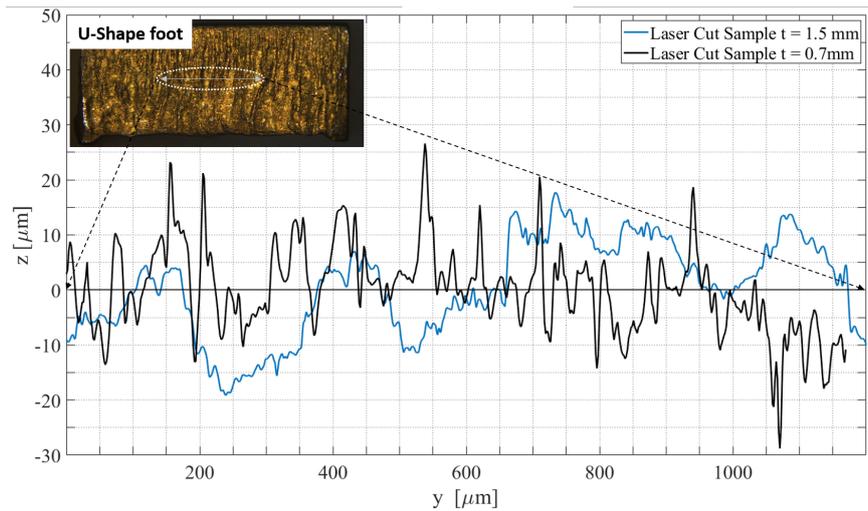


Fig. 6: Cu U-shapes surface roughness

Apart from the aforementioned SBPC application, this process could be also beneficial for split-output type power modules where the half bridge topology is divided in two switching cells consisting of a transistor and a diode. The advantage is to decouple the switching cells isolating the transistors from induced dv/dt and thus preventing false turn on and avoiding conduction through body diodes. The two outputs are connected together by using two discrete inductances [17] [18] [19]. The possibility to integrate these inductances directly on the power module, by using the proposed method, would result in a system volume reduction and enhanced thermal management.

In order to exclude the negative effect of the multiple solder joints on the DC resistance, hence on the inductor efficiency, a comparison has been carried out between the experimental results and FEM simulation where the contact areas between Cu U-shapes and DBC have been modelled as they were ideal, i.e. with no contact electrical resistance. The inductor impedance has been measured by using E4990A Keysight impedance analyser under an excitation of 20mA. The measurements are compared to FEA results and shown in Fig.8b. Below 100 kHz, the measured resistance values match the FEA results with an error of 1%, hence it is possible to conclude that the soldered joints do not affect the efficiency of the inductor.

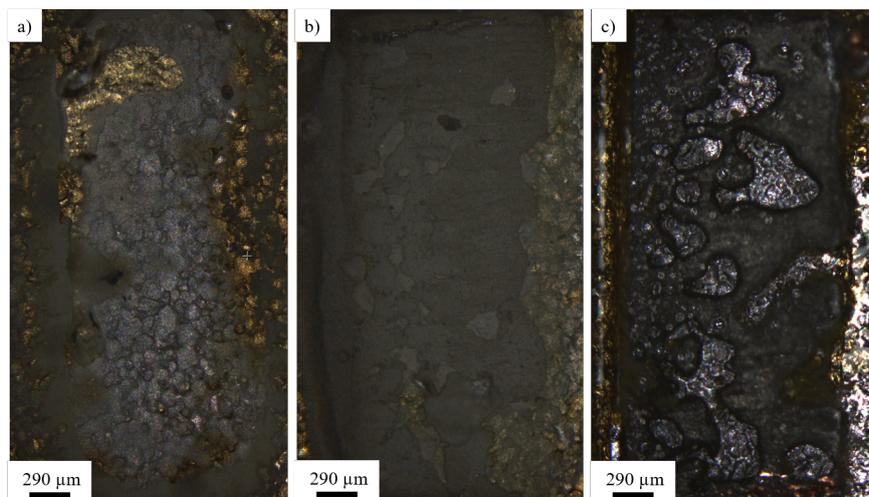


Fig. 7: Optical microscope images of the bonding area on the substrate after shear test a) Pressure assisted sintered joint, b) Pressure-less sintered joint, c) soldered joint

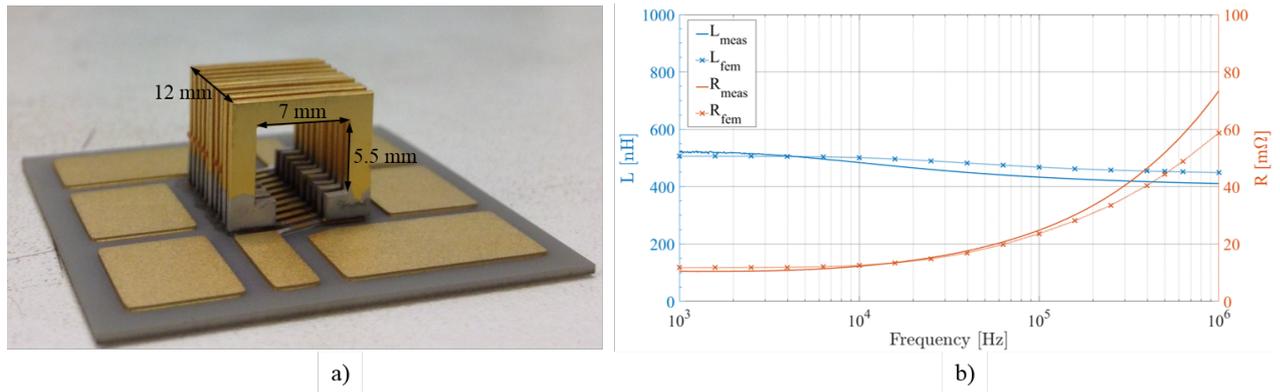


Fig. 8: Soldered integrated inductor, a) sample, b) impedance measurement compared to FEM results

Conclusions

A new manufacturing technique for integrating high current density windings on substrate by bonding individual copper U-shapes has been investigated. Preliminary simulation results show its effectiveness from a thermal point of view: the peak temperature is not dependant to the number of turns resulting in an additional degree of freedom in the passive component design stage. The extreme importance of inductor integration on power module substrate for converters in package and inteligent power module has been discussed. In additon to these applications, the proposed technique may be important for split-output type power modules where the additional inductances can be embedded in the power module.

Three different bonding techniques have been investigated to bond the Cu U-shapes: soldering and Ag pressure-assisted and pressure-less sintering technologies. It is worth noticing that all of them can be carried out by an automated procedure (e.g. by using pick and place machines and die bonders) that may be included along with the power module manufacturing process. In this particular application, soldered samples showed a stronger bond-line compared to Ag sintered samples and that can be attributed to poor finishing of the bonding surfaces. Indeed, the surface roughness of the laser cut Cu U-shapes is disproportionate to accomodate the particle size of the silver paste that was used.

Finally, a ten turn air-cored inductor has been manufactured with the proposed technique, using soldering technology. This proves the consistency of the proposed manufacturing route, showing that its possible to produce components by using thin copper parts (e.g. $700\ \mu\text{m}$) with a considerably small spacing (e.g. $300\ \mu\text{m}$). This first experimental result highlights both the thermal and mechanical benefits of such an integrated structure. The impedance measurement, compared to the FEA simulation, allows to exclude any negative effect of multiple soldering on the DC resistance of the inductor.

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