A new base plate concept on the basis of aluminium-copper clad materials

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Abstract

Power electronic applications for hybrid as well as for electric vehicles have a tendency to be based on liquid water cooling system in order to optimize the power density and keep the system compact. In this paper, we present a new concept for a cold plate, based on a new aluminium-copper (AlCu) clad substrate with copper on the top for soldering and a structured aluminium lower side for cooling. This solution is cost efficient, dispenses with nickel plating and helps to reduce the weight of the application. The analysis shows that the thermal performance of the AlCu-clad material is more than 9 % better than an adequate aluminium configuration.

1. Introduction

For automotive applications in electro/hybrid vehicles, power modules with pin fin structure are often used. They are very compact and have an excellent thermal performance, so that high power densities are possible. Furthermore a pin fin cooling plate for direct fluid cooling is a cost intensive module component as the price is directly coupled to the high market prices of raw material like copper or Aluminium- Silicon- Carbide (AlSiC) as well as to the production costs. For the base plate production, different technologies are available like cold forging, Metal- Injection- Molding (MIM), Ceramic- Injection- Molding (CIM) and deformation techniques like peeling or rolling. Furthermore base plates with cooling structures (Cu, AlSiC) are subjected to a cooling liquid so that chemical reaction like corrosion could reduce the lifetime expectation. To avoid this degradation process, a further process step is needed e.g. nickel plating.
An interesting solution for this problem could be an aluminium-copper clad material. The two metal layers are characterized by a high adhesion and are bonded by a combination of rolling and annealing [1].

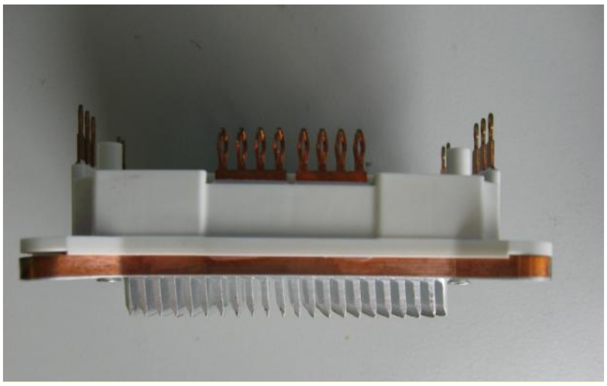

Fig. 1 Base plate with AlCu-clad material and fin structures.

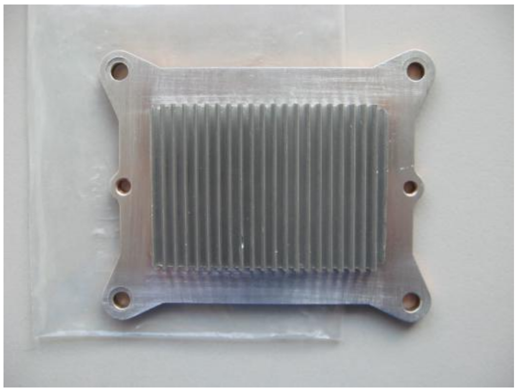

Fig. 2 Fin structures on the lower side of the base plate for direct cooling.

Both interfaces of the clad substrate are essential to functionality (reliability) as the top side is used for soldering directly on copper and the aluminium layer is structured by special de-

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formation technology [2]. An example could be found in Fig.1 and Fig. 2, showing a prototype of Infineon's HybridPACK™ 3 with an AlCu-clad base plate with straight fin geometry.

2. Thermal analysis of aluminium-copper clad materials

A cold plate on the basis of aluminium copper clad substrates is an interesting concept to overcome the problem of corrosion and to reduce the high material costs. But in turn the reduction of the copper volume impacts the thermal resistance (R_{th}), so that the chip temperature is increased and the reliability performance is lower.
Thus, in the first step, a simplified analysis of an Al-Cu clad material is done to figure out the differences between base plates made of Aluminium, copper and AlCu-clad material.
The thermal resistance of a power module is determined by different material layers. The heat, generated in the silicon chip, diffuses through the chip soldering, the DCB (Direct-Copper-Bond) stack and the system soldering and is transferred from the cooling structures of the base plate into the fluid, see Fig. 3 a). In case of a directly cooled module the thermal resistance is defined by (1), where T_{chip} is the chip temperature, T_F is the fluid temperature and the dissipated power is calculated by the saturation voltage of the IGBT chip ($V_{CE,sat}$) and the collector current I_C. The equivalent circuit of the power module is shown in Fig.3 b) and includes the thermal resistance as well as the thermal capacitances in a parallel arrangement. For a first estimation of the R_{th}, we assume a highly efficient fluid cooling, so that heat spreading is negligible. Under this condition we can calculate the thermal resistance of a material system with different homogenous layers with formula (2) where d_m is the thickness of the layer, λ_m is the thermal conductivity and A_{chip} is the chip area. The formula can be subdivided into three parts: the DCB stack (**I**), the base plate without pin fin structures (**II**) and an expression for the heat exchange (**III**).

$$R_{th} = \frac{T_{chip} - T_F}{I_C \cdot V_{CE,sat}} \tag{1}$$

$$R_{th} = \underbrace{\sum_{m=1}^{DCB} \frac{d_m}{A_{chip} \cdot \lambda_m}}_{\mathbf{I}} + \underbrace{\frac{d_{BP}}{A_{chip} \cdot \lambda_{Cu}}}_{\mathbf{II}} + \underbrace{\frac{1}{A_{chip} \cdot \alpha}}_{\mathbf{III}} \approx \sum_{m=1}^{DCB} \frac{d_m}{A_{chip} \cdot \lambda_m} + \frac{d_{bp}}{A_{chip} \cdot \lambda_{Cu}} \tag{2}$$

$$R_{th}(t_{Al}) = \sum_{m=1}^{DCB} \frac{d_m}{A_{chip} \cdot \lambda_m} + \frac{d_{bp} - t_{Al}}{A_{chip} \cdot \lambda_{Cu}} + \frac{t_{Al}}{A_{chip} \cdot \lambda_{Al}} \tag{3}$$

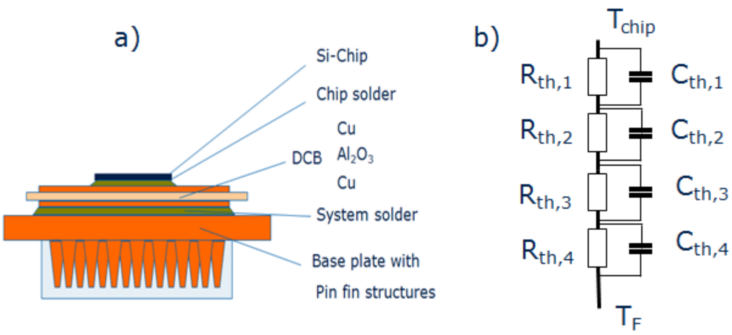

Fig. 3 a) Simplified cross section of a power module b) The equivalent circuit for the heat transfer, including the thermal resistance and the corresponding capacitances in parallel arrangement

The heat transfer coefficient is defined as α and d_{bp} is the thickness of the base plate. If we assume a high heat transfer coefficient in a range of 10000 W/Km^2, the contribution of the

third term can be neglected so that a simplified expression without a heat transfer coefficient is achieved. In an aluminium-copper clad system, the base plate has to be subdivided into different parts, one for the aluminium (thickness t_{Al}) and the second one for the copper layer (thickness d_{bl}-$t_{Al.}$) Taking these modifications into account we find the following expression (3) for the total thermal resistance in dependence on the thickness of the aluminium layer t_{Al}. In Fig. 4 the total R_{th} of a power module with a copper base plate is calculated with formula (3) on the basis of typical data for heat conductivity and layer thicknesses. The base plate, the system soldering and the Al_2O_3 ceramic are the dominant components, especially the ceramic with a contribution of 44 % to the total R_{th}, due to a weak heat conductivity to be from 20 to 30 W /mK. The total thickness of the base plate is set to 4 mm. The same calculation for an aluminium configuration is shown in Fig.5. For the aluminium copper clad substrate t_{Al} is set to 1.5 mm and a copper layer is 2.5 mm. The R_{th} of such a clad system is decreased respectively a aluminium configuration and the contribution of the other parts of the R_{th} are increased correspondingly, see Fig.6.
In Fig. 7, the R_{th} is plotted versus the thickness of the aluminium layer. The difference between a copper and an aluminium configuration is found to be 22 %. The calculation results show that a small aluminium layer of 1.5 mm amount to a R_{th} reduction of 7 % in comparison with a copper configuration. And in addition to this, an aluminium layer of 1.5 mm corresponds to a reduction of copper by 37 %.

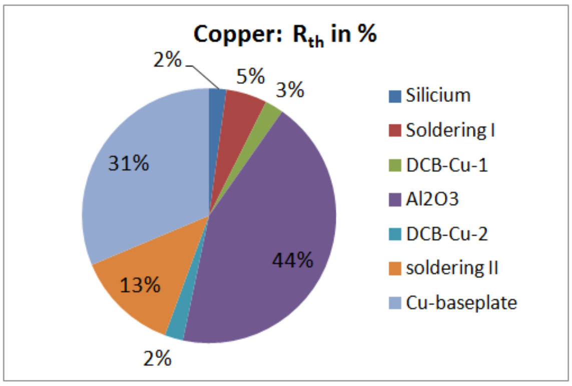

Fig. 4 The relative R_{th} in % for modules with copper base plates.

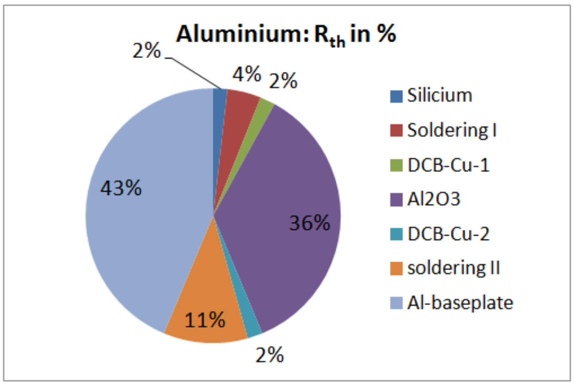

Fig. 5 The relative R_{th} in % for modules with aluminum base plates.

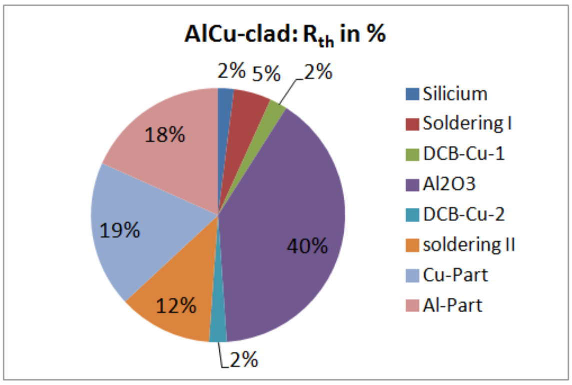

Fig. 6 The relative R_{th} in % for modules with AlCu-clad base plates (1.5 mm Al, 2.5 mm Cu)

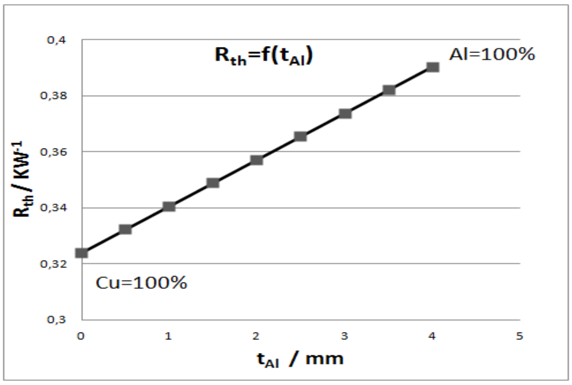

Fig. 7 The absolute R_{th} is plotted versus the thickness of the aluminum layer. The total thickness d_{bp} is set to 4 mm

3. Concept of an aluminium-copper clad system

There are different ways to implement the idea of an aluminium-copper clad system. But not all clad systems are suitable for automotive applications, as very strict requirements are imposed on power modules to fulfil the demand for a high life time expectation. An AlCu-clad base plate can be fabricated e.g. with cold forging, including aluminium and copper material. The clad material and the cooling structures are fabricated in a single process step. Alternatively it is possible to bond copper on an aluminium surface with other techniques like cold-spray or deposition [3].
In this paper, we separate the production of aluminium-copper clad material from the production of cooling structures in order to optimize the characteristics of the material. For the clad material system we use a technique, based on rolling and diffusion annealing. This technique affords a high adhesion between the material layers and promises an acceptable reliability for automotive applications. The cooling structure can be generated in a second step by applying well known deforming technique, e.g. peeling or rolling. The adhesion between the layers is defined by the plating process and a diffusion annealing step at high temperature. In the plating process the material layers are pressed together in order to get a first bond connection between the layers (Van-der-Waals-Interaction).

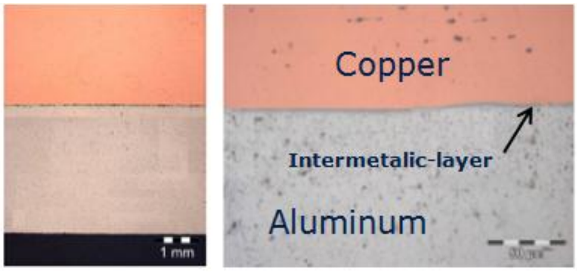

Fig. 8 A Cross section of the clad material: the different materials and the inter-metallic layer can be recognized clearly.

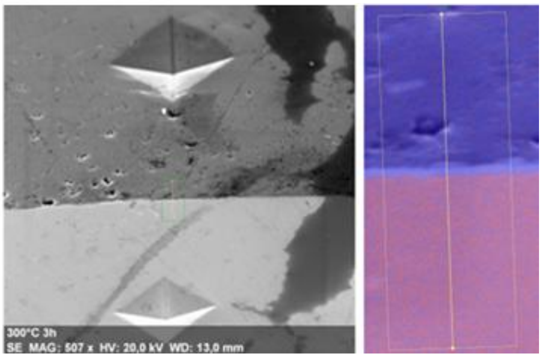

Fig. 9 The Vickers hardness of the clad material is measured and a line scan with SEM is performed.

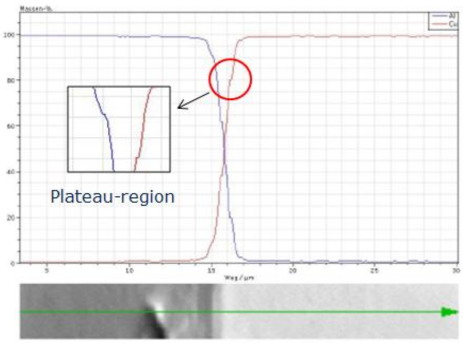

Fig. 10 Result of a SEM line scan. On the left axis the relative mass concentration is plotted versus the position of the electron beam.

At a specific temperature, the formation of inter-metallic phases starts, so that a connection similar to diffusion welding is formed. The growth of inter-metallic phases is strongly driven by a diffusion process, in which materials from both interfaces are involved. The thickness of inter metallic layers can by described by a $\sqrt{T}$-law, being typical for diffusion processes, where T is the time for the high temperature storage. It is well known that diffusion processes are thermally activated, so that temperature is a further parameter for the adjustment of the optimal thickness and in turn the optimal adhesion between the material layers. In contrast to aluminum and copper, the Vickers hardness of inter metallic phases is about 600. In comparison to this, aluminum has a value to be from 39 to 45 and the hardness of

copper is about 95. With a SEM (Scanning-Electron-Microscope) analysis it is possible to detect inter-metallic phases via a line scan, see Fig. 9 and 10. The method is based on the interaction between a highly focused electron beam and a selective detection of X-ray signal. The mass concentration within the inter-metallic layer changes rapidly due to the diffusion process started during the diffusion annealing step. The plateau-regions in signal slope point to the formation of different inter-metallic phases, see Fig. 10. An investigation with EDX (Energy dispersive X-ray Spectroscopy) verifies that the inter-metallic layer is made of different chemical compounds.
In TST (thermal shock test) the reliability of the new material system was under investigation. The module was subjected to 1000 TST cycles to observe the degradation of the system soldering and of the bond connection between aluminum and copper where one TST-cycle goes from -40°C up to +150°C. No degradation effects could be recognized.

4. Measurements and Devices Under Test (DUT)

For the production of an aluminum-copper cold plate it is possible to use a special deformation technique [2] to structure the aluminum layer for getting Pin Fin (PF) or fin structures. Other techniques like forging, peeling or rolling are also options for structuring the clad substrates. For a hydrodynamic and thermal characterization and optimization, we take different geometries and structures densities into account, see Fig. 11. Two different fin per inch (fpi) values with different gaps between the cooling structures are considered.
In preliminary studies we investigate the thermal performance of different cooling structures to evaluate the best configuration for an AlCu-clad application. The cold plates are integrated in a cooler using a 50% water glycol mixture as cooling liquid. The thermal resistance as well as the pressure drop Δp are measured as a function of the fluid flow.

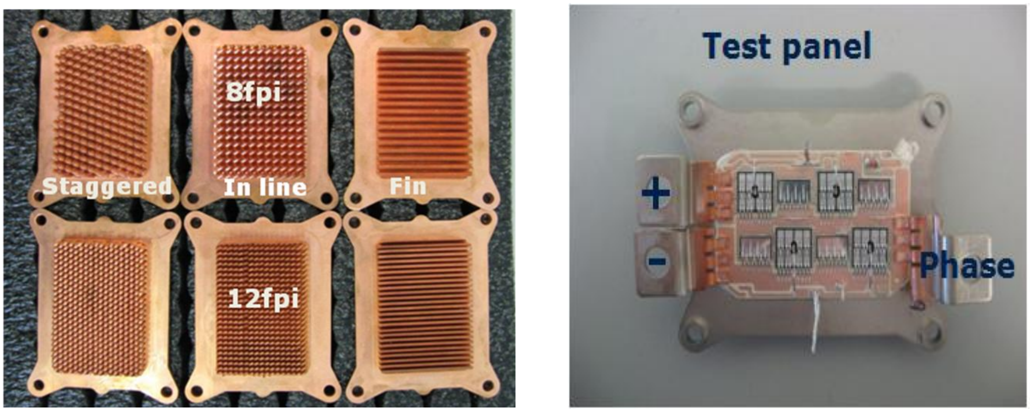

Fig. 11 Different cooling structures are tested under the same condition. The DUT for R_{th} measurements is show in right picture

The diagram in Fig.12 shows a clear R_{th}-ranking starting with the staggered PF (1) inline PF (2) and the straight fin geometry (3), for further technical details see e.g. [4]. The staggered PF with 8 fpi combines a good thermal performance with an acceptable pressure drop, shown in Fig. 13. For further investigations we used a staggered PF (8 fpi), as they fulfil the common need for gaps bigger 1 mm to protect the cold plate against clogging. In Fig. 14 the thermal performance for a staggered PF (8 fpi) geometry is studied for aluminium, copper and an AlCu-clad configuration. The difference between copper and the clad material is about nine percent. Between aluminium and copper we find a delta of 19%. These findings are in a good accordance to the theoretical investigation at the beginning of the discussion. The AlCu-clad cold plate achieves a significant better thermal performance than an adequate pattern made of aluminium (10%). This difference between copper and AlCu-clad material shows that the contribution of the pin fin structure to the total R_{th} (DCB, copper layer, Pin Fin) is very small. For applications justifying a higher price, higher weight and an additional process step (nickel plating) the copper configuration provides naturally the best thermal performance, Fig.14.

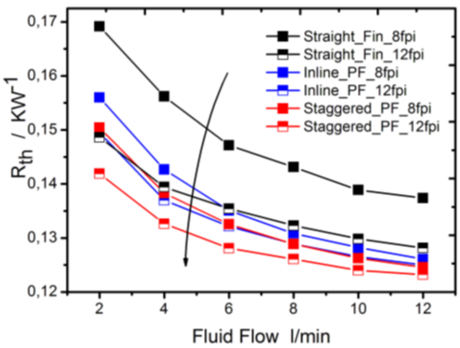

Fig. 12 Thermal resistance versus the fluid flow (different geometries).

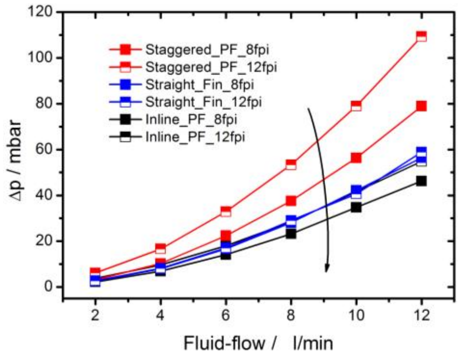

Fig. 13 Pressure drop versus the fluid flow (different geometries).

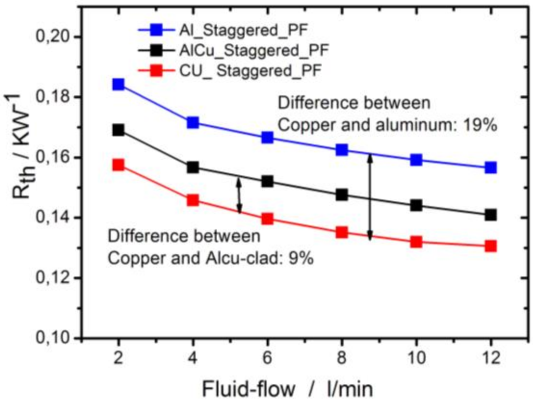

Fig. 14 The thermal resistance R_{th} is plotted versus the fluid flow. Different material systems are under consideration

5. Conclusions and Summary

A new concept for an AlCu-clad base plate is presented. It is based on an AlCu- clad material bonded by rolling and annealing. The bond connection between aluminium and copper is characterized by a high adhesion and does not delaminate under TST stress conditions including 1000 temperature cycles from -40°C up to 150°C.The comparison between an aluminium and AlCu-clad cold plate shows a significant improvement of the R_{th} of 10%. The achieved weight reduction is about 30%. These investigations verify that all advantages of a clad concept can be used without losing too much thermal performance respectively a copper configuration.

6. Literature

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[3] Y. Kuromitsu at al. paper 11.1, CIPS 2010, 2010 Nueremberg/ Germany
[4] IEEE Transaction on components and Packaging technologies, vol. 23, No.1, 2000