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REPORT

The use of printed thermal transfer pastes to improve thermal dissipation on printed circuit boards

Characteristics, application, rationalization and cost saving potential, e g. in the field of LEDs and high current devices

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Introduction

The density of the electrical component assemblies on printed circuit boards is constantly growing because more complex circuits have to be located in smaller areas (miniaturization). This development and the use of high-performance components that sometimes produce a high loss of power in form of heat, necessitate a specific dissipation of the generated heat away from the source to the environment. The failure to apply this technology would result in an overheating of the components that would entail malfunctions and, in the worst case, even a destruction of the component. In some applications, matters are made worse by the fact that elevated temperatures already exist at the pcb's place of operation.

To achieve a good heat dissipation the use of metal heatsinks is common. These heatsinks are mostly metallic cooling elements which are somehow connected to the pcb and ensure on the one hand the heat dissipation from its source owing to the good heat conduction of metals and, on the other hand, enable the dissipation of the heat to the environment because of the large surface towards the ambient air.
This report is about two printable thermal transfer pastes, firstly the thermal interface paste ELPEPCB® TIP 2795, and secondly the heatsink pastes of the series ELPEPCB® HSP 2740, which permit to optimise thermal management.

Theoretical principles of heat conduction and heat dissipation

Heat conduction is the transport of energy as a result of atomic and molecular interaction. It is caused by an uneven temperature distribution and, in compliance with the 2nd basic principle of thermodynamics, it always flows from the hot to the cold element. The capability of conducting heat – the thermal conductivity – is a specific characteristic. Metals have the best thermal conductivity, followed by inorganic solids. Next in line are organic solids and liquids. Gases have the poorest thermal conductivity. Table 1 contains some figures regarding this subject.

	λ in W/m K
tin, aluminium, copper	64, 200, 400
air	approx. 0.02 - 0.03
polymers	approx. 0.2 - 0.4

Table 1: Thermal conductivity λ of various materials

The thermal resistance (R_{th}) of a body decreases in proportion to increasing thermal conductivity (λ) and contact area (A); it increases on increase of thickness (t).

$$R_{th} = \frac{t}{\lambda \bullet A}$$ **Equation 1**

The thermal resistance R_{th} defines the specific resistance and is characteristic for a given material.

The thermal impedance or the thermal impedance resistance R_{Θ} is similarly characteristic as the thermal resistance, but it includes the interface and its heat transition resistance:

- the mode of contact areas generated between heat source and heatsink
- the contact pressure
- the surface of Thermal Interface Material (TIM)

$$R_\Theta = R_{th} + R_{j1} + R_{j2}$$ **Equation 2**

R_Θ = thermal impedance resistance
R_{th} = thermal resistance
j = junction, interface
R_j = heat transition resistance

An important aspect in this set-up is the heat transfer resistance between two bodies . Thus one rod with a length of 10 cm has a better thermal conductivity than two rods of the same material of 5 cm length, which are in direct mechanical contact. In thermodynamics, one calculates with so-called heat transfer coefficients or heat transfer resistances in this case. This is explained by the roughness of every body surface. In case of a direct contact of solid surfaces, the "real" contact area is reduced by microscopic "air inclusions" so that the heat can flow through a reduced area only.

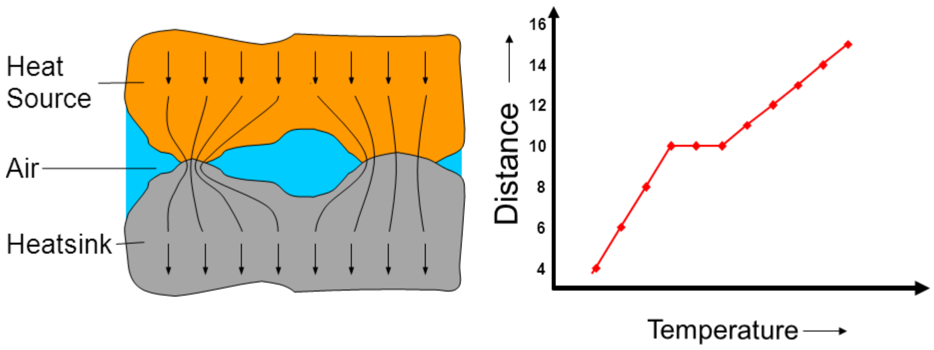


Figure 1: Classical heat transition

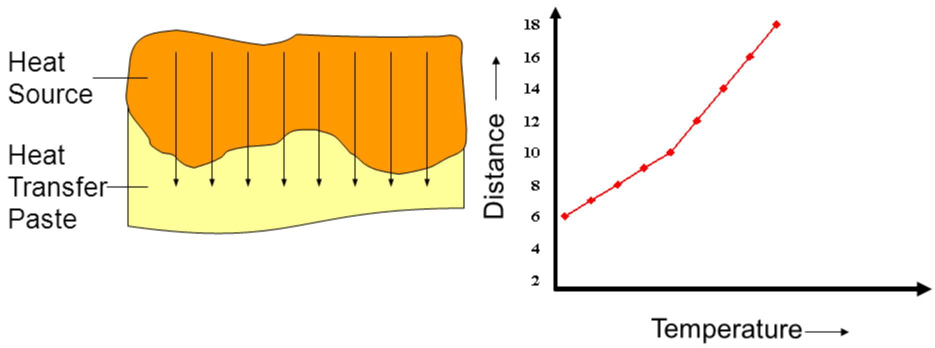


Figure 2: Heat transition with printed heat transfer paste

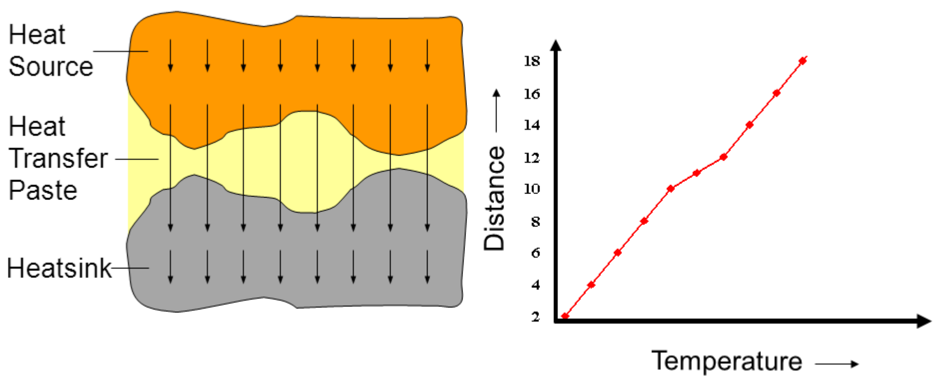


Figure 3: Heat transition with a combination of heat transfer paste and heatsink

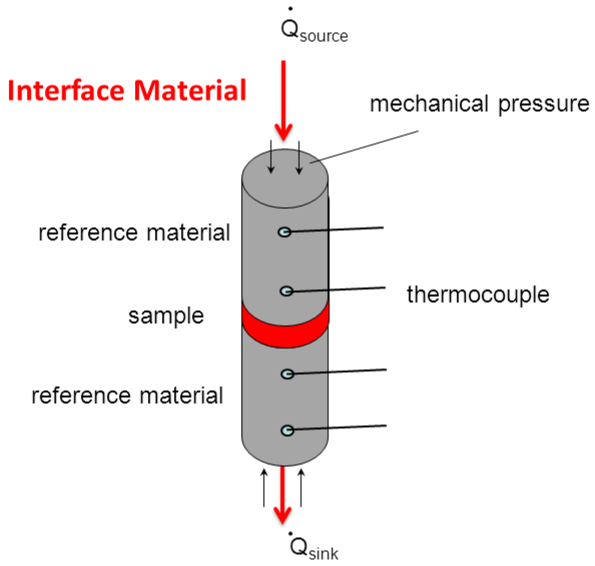
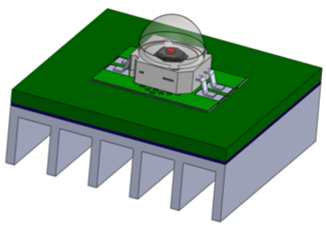


Figure 4: Systematic illustration of measuring Interface Materials
(Source: ZFW - Zentrum für Wärmemanagement Stuttgart)

The use of thermal interface pastes in **I**nsulated **M**etal **S**ubstrate (IMS) applications

The heat conducting path in an IMS-PCB

In a typical IMS application the heat of a component, e. g. of a high power LED, is conducted into an aluminium layer of the printed circuit board and distributed. It might be necessary or advantageous, however, to connect a further cooling element.



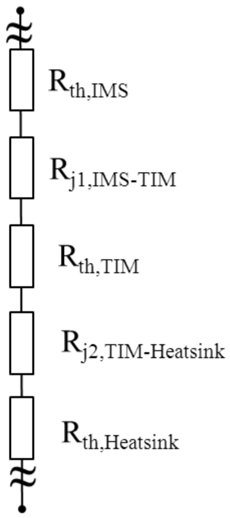


Figure 5 left: Example of a LED assembled IMS Substrate
(Source: ZFW - Zentrum für Wärmemanagement Stuttgart)
right: equivalent circuit diagram of the heat path from the IMS to the heatsink

Simplified schematic picture:

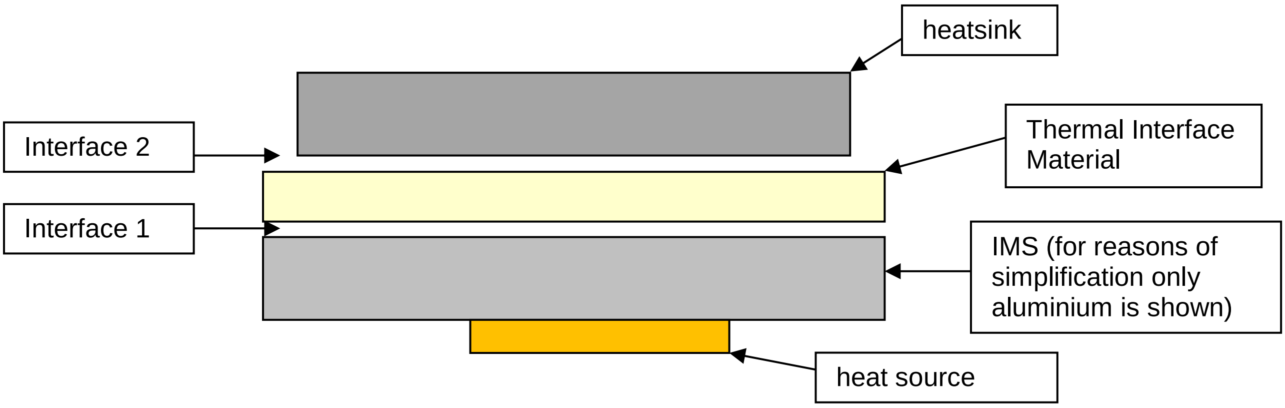


Figure 6: schematic construction of an IMS pcb (simplified illustration)

On the basis of an analogue analysis of an electrical circuit, the heat resistances can be interpreted as resistances in a circuit that are either connected in parallel or in series. Special attention must then be paid to the highest heat resistances and heat transfer resistances, which ultimately determine the entire heat flow. Along the lines of the graph the following heat conducting path can be recognized:

$$R_{total} = R_{alumina\ IMS} + R_{Interface\ 1} + R_{TIM} + R_{Interface\ 2} + R_{alumina\ cooling\ element}$$ **Equation 3**

In this context TIM describes all thermal interface materials like pastes, greases, adhesives and foils. The heat resistance of aluminium and TIM is known resp. can be measured.

The heat resistance of the two interfaces should be studied more closely. The higher the contact pressure, however, the better the connection between the layers and the lower the heat resistance. When using heat conductive foils, however, the thermal resistances of both interfaces have to be considered. Depending on roughness of the foil surface and in particular on the elasticity module more or less relevant resistances will be the result.

On a complete wetting, i. e. as seen in wetting fluids, the thermal resistance in the interface is virtually zero.

$$R_{\Theta} = R_{th} \quad (R_{j1} + R_{j2} \text{ assumed value} = 0)$$ **Equation 4**

j1 + j2 = wetted fluid interfaces

Consequently, when using liquid thermal interface materials like greases or thermal conductive adhesives, the thermal resistance of the interfaces 1 and 2 is not significant.

Liquid pastes, which are screen printed on the printed circuit board and then cured, wet like a fluid in interface 1 and behave like a thermal conductive foil in interface 2. Thus interface 2 has to be included in considering the heat conductive path.

$$R = R_{th} + R_{j2} \ (R_{j1} \text{ assumed value} = 0)$$ **Equation 5**

j1 = wetted fluid interface

Comparison of different Thermal Interface Materials (TIM)

Besides the examination of the thermal interface resistance, special attention should also be given to the TIM material itself. Of course the thermal conductivity is a very important parameter but the layer thickness of the TIM within the application also is of high relevance.

When comparing various TIMs all elements of Equation 2 (see page 3) have to be considered likewise.

Next to the thermal management further factors will be important for the selection of a TIM.

The presently most used technologies which are applied to fill the gap between the typical roughness of the heatsink and the substrate are the following:

- application of electrically non-insulating thermal grease on the surfaces
- by means of dispensing or screen printing
- use thermal pads

Both of them are production steps done after the component soldering process.

Thermally conductive grease

Thermally conductive grease improves the efficiency of a heatsink, but it is subject to a kind of “pump out effect” related to temperature variations. Such effect causes a moving of the grease away from the original requested position, reducing - in long term - its efficiency.

Furthermore, the application of such grease is not one of the most preferred process steps by the operators as it is not a very clean operation. Generally cost level is quite low.

Thermal pads

Thermal pads are a pre-formed square or rectangle of solid material which are cut to fit. They are made of solid material having the same function as thermal grease and can be electrically insulated or not, adhesive or not.

As an alternative to thermal grease they are cleaner, no “pump out effect” occurs and generally they are easier to install.

However, thermal pads conduct heat less effectively than a minimal amount of thermal grease, as their typical thicknesses are higher than 120 µm, but most commonly used 200 µm or more.

Generally cost level is much higher compared to thermal grease. Besides the pre-cuts are done from dimensionally standardised rolls, so that the total cost of such thermal pads is strongly influenced by the dimensions and shapes of the parts to be interfaced.

Screen printable solder resistant Thermal Interface Paste (TIP)

A new technical advanced solution is a screen printable TIM, a paste which is electrically insulating and soldering resistant.

Such a product has been developed in partnership between Germany based Lackwerke Peters GmbH + Co KG (manufacturer of high tech coatings for electronics) and Italy based Serigroup s.r.l. (printed circuit board producer for power electronics).

Application and curing is done by the substrate manufacturer on the bare pcb selectively in the specified layout, prior to soldering. In this way, the end users will receive the pcbs with the TIP already “on board”.

The typical end thickness after screen printing and curing is between 50 and 70 µm.

Since there is no pump out effect when using the Thermal Interface Paste TIP, the thermomechanical decoupling properties are ensured even in permanent thermal cycles.

The final total cost will be reduced to a large extent compared to the thermal pad because of the following reasons:

- 100% material yield due to the selective screen printing process
- no pre-cutting costs
- reduction of process steps in the assembly, only soldering and mechanical fixing afterwards.

Thermal-mechanical decoupling

Besides the optimized heat conduction the use of Thermal Interface Material also has a strong impact on the thermal-mechanical decoupling.

An important aspect in this context is the shear modulus of the Thermal Interface Material.

During their lifetime electronical assemblies go through various temperature ranges. For assemblies with a coupled heatsink the thermal expansion of the pcb and heatsink materials must be taken into consideration in more detail. As they may consist of different materials, their thermal expansion coefficients (CTE) are also different. When connecting pcb and heatsink the assembly will be exposed to stress and a possible deformation due to the different expansions and contractions caused by CTE, the so-called thermal mismatch. Thermal Interface Materials on a silicone basis with a low shear modulus, reduce this stress at a considerably higher degree than materials with a high shear modulus.

A printed Thermal Interface Material, e. g. a TIP, is connected to the pcb only, whereas the heatsink material will be pressed on on the other side only. Thus the stress will be reduced once again. The shear modulus of a Thermal Interface Material is determined by the structure of the material, including polymer matrix, crosslink density, molecular weight and filler.

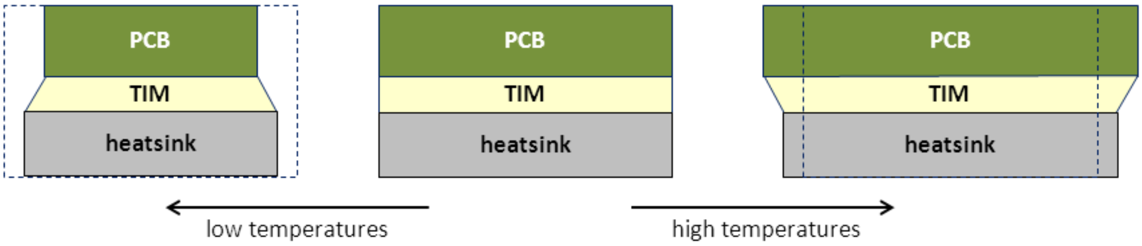


Figure 7: Different expansion and contraction of pcb and heatsink, connected via TIM, during thermal cycling

The use of printable heatsink pastes in double side pcbs

In pcb technology, the heat source and possible surface for heat dissipation - the heatsink - are frequently located on different sides of the printed circuit board. The pcb materials have a relatively low thermal conductivity ranging from approx. 0.3 to 0.5 W/m K. By interlayering up with materials of a good thermal conductivity - normally metals - one achieves good heat dissipations in case of Metal Core Boards. Another method is to link the heat sources to the heatsink by means of so-called heat couplers (Figure 8).

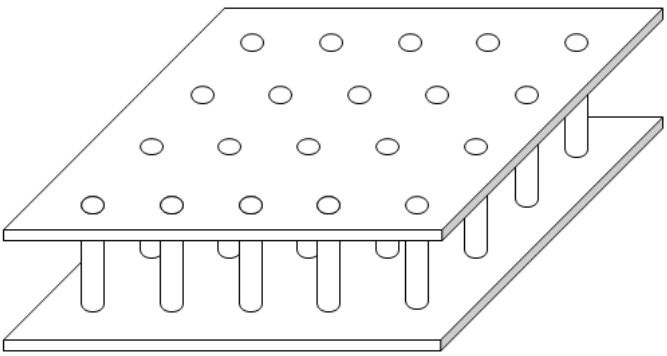


Figure 8: Diagram of a heat coupler

The heat couplers consist of a number of heat vias between two contact areas, whereby, the heat source and the heatsink must be connected with the lowest heat transfer resistance. In the construction of the heat couplers, the metallic plated-through hole determines the overall thermal resistance of the heat coupler. A higher number of plated-through holes reduces the thermal resistance as does an increasing thickness of the metal heat via.

The conventional attachment of metallic heatsinks to the heat coupler is effected, for instance, by means of bonding (Figure 9). A required transfer with good heat-conducting properties from the heatsink via the metallized heat vias (1) of a number of heat vias, at which the dissipated heat from the front of the printed circuit board (6) (B side) "arrives", is reduced by the (bonding) film (3) between the heatsink on the reverse and the metal cladding as well as by the relevant specific heat transfer resistances between printed circuit board and bonding film and between bonding film and heatsink.

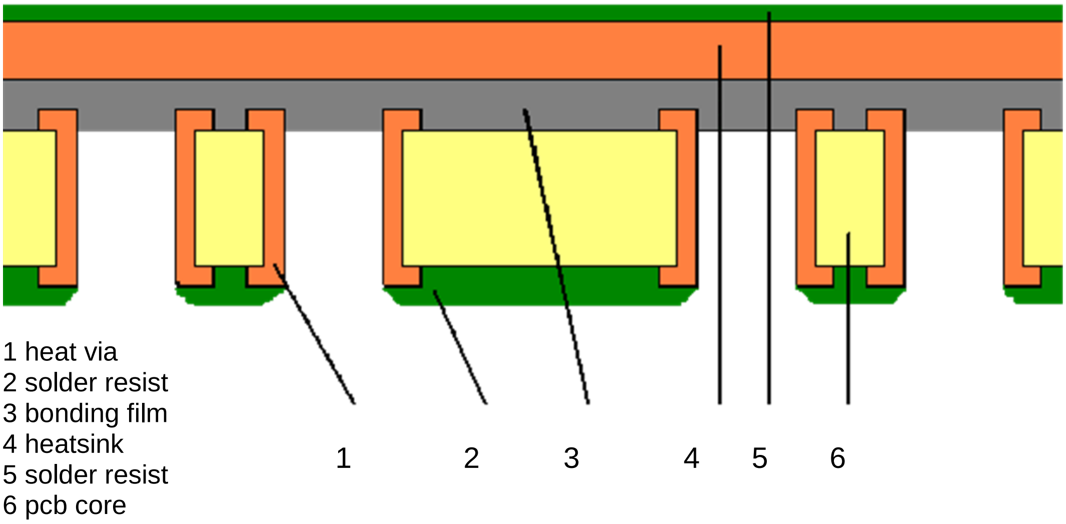


Figure 9: The "classical" heatsink of a double-sided, plated-through printed circuit board - also applies to multilayers

Process steps in heatsink assembly

The technology described for the assembly of bonded heatsinks has the disadvantage of constituting a very labour and thus cost intensive procedure. To begin with, the metal foils serving as heatsinks have to be punched into corresponding shapes which requires the manufacture and operation of respective punching tools. A double-sided bonding film must then be applied to the punched-out heatsink which afterwards must be positioned on the printed circuit board. Following the positioning process on the pcb, the metal foil has to be coated with corresponding coating systems for electrical insulation and protection from corrosion. For this process, defined coating thicknesses with the matching electrical and dielectric properties are required. As these heatsinks are usually several 100 µm high, an adequate edge coverage cannot always be realized with sufficient process safety. As a rule, a surface pre-treatment of the metal foil is required additionally in order to produce a good adhesion which, for instance, is required for a subsequent wave or reflow soldering process.

As a rule, the process steps listed cannot be automated and, therefore, have to be performed manually. Thus, these operations are highly time and cost consuming and the result obtained is not equal to the required precision of a mechanical production.

The printed heatsink

The function of a printed heatsink generally corresponds to that of a heatsink made of metal foil.

As illustrated in Figure 10, the printed heatsink enables the heat transfer resistances between heatsink and bonding film, between bonding film and pcb as well as between bonding film and heat via; finally to be dispensed with, also the bonding film itself is omitted. Owing to the printing process, the plated-through holes of the heat coupler - the heat vias - are filled and the number of heat transfer resistances is reduced. There is an optimum between the interface printed heatsink and the heat coupler.

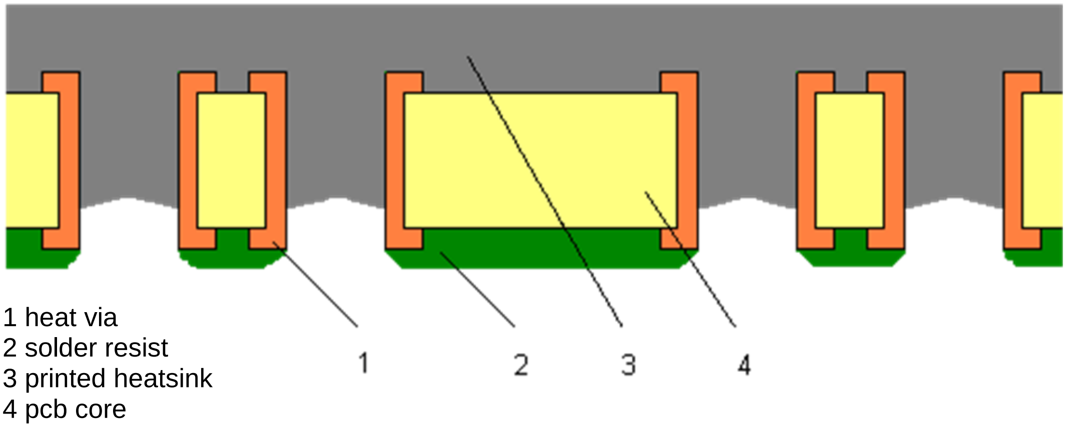


Figure 10: The printed heatsink of a double-sided, plated-through printed circuit board - also applies to multilayers

Another particular advantage for the heat dissipation is the fact that the printed compound partly fills the existing heat vias (see Figure 10). This enlarges the contact area between the heat dissipating heatsink and the heat coupler on the printed circuit board. This enlargement of the contact area considerably favours the heat transport because the heat transfer resistance decreases as the contact area increases. A roughly estimated calculation results in an increase of the contact area of more than 50% when the heat vias are filled to 75%. This value may slightly vary depending on the pcb layout and should be regarded as a reference quantity only. Moreover, the heat transport in the heat via determined by convection is replaced by the more efficient heat transport in a solid medium.

In its lateral expansion the heatsink reaches beyond the area of the heat coupler. In the case of the printable heatsink the extension for the heat spreading area that projects beyond the heat couplers has to be optimised in tests; the existing layout may have an influence on the lateral heat spread. Owing to the non-metallic character, the lateral heat spread in the printed heatsink is lower than in metal foils. A simple substitution of metal foil for the printed heatsink is impossible without a thermal analysis.

The printable heatsink can also be employed where the heatsink represents a part of the conductive pattern. In this case, the heat dissipation area can be reduced in the conductive pattern and replaced by a printed heatsink. Experiments have proven that, in this case, more than 50% of the previously required copper surface can be saved. Since the printed heatsink is not electrically conductive, conductor spacings towards the heatsink can be reduced and overprinted with the heatsink.

The target of another examination is the optimum attachment of the heat source - i.e. with lowest heat transfer resistances - to the heat coupler. The best thermal attachment, for instance, could be achieved by soldering; even a bonding agent or partial potting with a casting compound with good heat-conductive properties could be employed. If the thermal attachment at this location is problematic, for instance above a large air space, this heat transfer resistance may become a restrictive factor in the heat transfer.

The entire system - heat source, heat coupler, heatsink - can be regarded as a series connection of resistances in which the maximum resistance will then become the limiting parameter for the heat flow.

More accurate calculations are feasible, but these are extremely complex. In the subject examination, the problematic nature has been reduced to an unidimensional heat flow. In practice - especially in case of multilayers - however, the influences of adjacent conductor groups have to be considered in the same manner as the heat flow parallel to the heat source. The electrical-thermal analogy continues to apply but is complicated by the nesting of a variety of series and parallel connections.

The heatsink paste can also be coupled directly to the heatsink. At best a thermal impedance of approx. 1 K x cm²/W can be achieved. Structures from the pcb cannot be levelled in all cases (combination with the Thermal Interface Paste, characterized by a more elastic and more plastic behaviour).

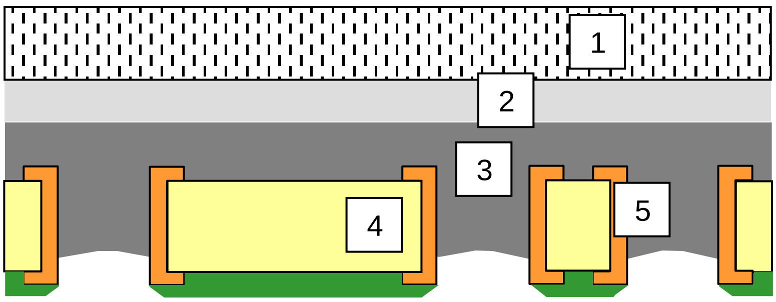
Combination of printed heatsinks and printed thermal interface materials

For some applications, such as street LED lighting or other power applications in which pcbs are under operative high voltage, a double insulation layer can be necessary or even required by law.

This situation can be solved by the combined application of the printed heatsinks and the screen printable TIM over the heatsink.

The hardness of the printed heatsink paste will efficiently support the application of the thermal interface paste.

For this purpose, the heatsink paste is used for filling heat vias and for heat spreading. The optimum connection to the heatsink is ensured by the Thermal Interface Paste TIP (Fig. 11).



1 = cooling element
2 = TIP (thermal interface paste)
3 = printed heatsink paste
4 = pcb core
5 = heat via

Figure 11: Combination of heatsink paste and thermal interface paste

The printable thermal transfer paste

Compared to alternatively used materials like greases, foils and adhesives, the printable thermal transfer paste has a number of advantages. Reference is made here to the simplified - in particular automatable - processes.

Structure of the printable thermal interface paste / heatsink pastes

The paste consists of special polymer matrixes so that the system can be applied to the printed circuit board by means of the screen or stencil printing process, it can be fixed, and thus will be functional after a thermal curing process. This polymer is filled with special, finely dispensed solid particles which ultimately ensure the required thermal conductivity. The ideal printable heatsink is available as a 1-pack system, is solvent-free and can be cured without any problems in usual curing units, convection dryers or IR drying units.

Properties of the printable thermal transfer paste

The application of the printable thermal transfer paste to the printed circuit board

The thermal transfer paste can be applied to a printed circuit board by means of the screen or stencil printing methods which normally used in pcb manufacturing. Printing is effected in the corresponding form; the desired form achieved is clean and well-defined with distinct edges/sides. The high definition and ease of printing make the presentation of any heat-dissipating areas on the printed circuit board possible. The coating thickness of the paste is variable over wide ranges fulfil various requirements. The thermal transfer paste can be applied to metallic surfaces directly, i.e. without insulation print or film, because it is an electrical insulator. Regarding its electrical properties (surface resistivity, tracking resistance, dielectric breakdown), the printed thermal transfer paste is identical to an insulating coating so that an additional insulating coating - both towards the printed circuit board and towards the environment - can be dispensed with. The printing process generates a high flexibility in the configuration of a large variety of heatsink geometries, because it only will be necessary to change the screens or stencils.

Solder resistance

Besides its thermal functioning, the printable thermal transfer paste is typically applied after surface finishing and before the assembling. Therefore, it has to be resistant to solder processes like wave soldering and reflow solder processes.

Further technical requirements

The demand for self-extinctive properties is another important basic requirement that is normally tested and certified as per Underwriters Laboratories Specification UL 94 V-0.

Cost saving potential

The use of printable thermal transfer pastes simplifies the production of printed circuit boards because this innovation particularly saves cost and time consuming process steps. In addition, automation in this section of production is feasible. All these reasons constitute a substantial cost saving. Another asset is the increased process safety which eventually has a positive effect on the cost side. A cost calculation, of course, varies from producer to producer but in any case leads to a positive result.

Just as an example, it is possible to skip the use of heatsinks in cases where the thermal properties of the substrate are not sufficient, but cooling elements are over performing (and costing) applications.

Conclusion

The principle field of application of the printable heatsink is where heat dissipation is feasible via a heat coupler to the "reverse side" of the printed circuit board and heat flows of about 2 W/m K occur. The printable heatsink is a special solution for thermal problems where the use of metal foils is too cost intensive or a metal foil cannot be used for reasons of layout configuration.

The printable heatsink can be successfully applied where the layout features copper surfaces as heatsinks. In these cases, a copper surface reduction by more than 50% is made possible by covering these surfaces with a printable heatsink. Here, an insulation coat could be omitted because of the insulating character of the heatsink.

The use of printable heatsinks constitutes an advantage not only for the pcb producing companies but also for the "users" of these printed circuit boards. Since the printed heatsink does not have any electrical conductivity, it stands out for an increased functional safety. Malfunctions caused by a possible short-circuit are impossible. Apart from its excellent adhesive strength, the printable heatsink also offers a weight saving compared to a classical metal body. The simplified printing process also makes totally different configurations of the heatsink possible. In addition, this method offers a fast change of formats for the heatsink.

Literature

For an overview of the standards and literature on the subject of thermal management, reference is made to a list, compiled by the Trade Association Electronic Design e.V.: "Selected literature references regarding the thermal management in components, on printed circuit boards, electronic assemblies and equipment" (FE-22-08).

Practical advice can be found in the seminar on the subject of "Thermal assembly dimensioning - simulation and measurement" by the ZµP-centre for microtechnical production at the institute for electronics technology of the Dresden Technical University.

Below please find some more literature references regarding thermal management:

EITI-Seminar - TU Dresden 10.02.2000

U.Grigull, H. Sandner
Wärmeleitung, Springer-Verlag, Berlin-Heidelberg-New York, 1979

H. Müller
Hochtechnology-Multilayer (Kapitel 4.8 Wärmeübertragung, Wärmesenken, Wärmekoppler), Leuze Verlag, Saulgau, 1988

J.R. Culham, P. Teertstra, M.M. Yovanovitch
The Role of Spreading Resistance on effective Conductivity in Laminated Substrates, Future Circuits International, 2000

Appendix

Explanations of indices and abbreviations contained in this report

TIM	thermal interface material
TIP	thermal interface paste
HSP	heatsink paste
PCB	printed circuit board
IMS	insulated metal substrates