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Heat Management in Printed Circuit Boards

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ABSTRACT
This report discusses the significance of heat management in the design of printed circuit boards (PCB). After an introduction into the basics of PCBs the crucial mechanisms of heat transfer are discussed with regard to significance and typical design parameters. Emphasis is laid on ways to determine conductive heat transfer. Here, common techniques as well as considerations on how to model PCBs for simulations are shown. Finally practical examples are given to illustrate the prior discussed aspects.

NOMENCLATURE
k	conductivity
t	layer thickness

Subscripts

avg	average
c	copper
e	effective
g	synthetic board
n	normal to the board
p	parallel to the board

INTRODUCTION

Printed circuit boards have been a milestone in the development of modern electrical applications. They allow for cheap and fast production of complex circuits on small areas and are widespread throughout technical systems. The basic structure consists usually of an isolating synthetic board on which a copper pattern is "printed" (discussion of actual production step not included here). This pattern serves to connect various subsequently installed electrical components. In more sophisticated designs several layers of copper patterns and isolating material are stacked to safe space.

PROBLEM STATEMENT

Every non-ideal electrical component conducting a current is a potential heat source. This is due to the fact that they include an electric resistance which converts the kinetic energy of electrons (current) into heat energy. This process is often referred to as Joule heating. Due to ever decreasing sizes of components and more advanced production technologies the general trend in PCBs is to arrange more and more components in small areas. This entails a higher concentration of heat sources on the board and thus enlarges the significance of heat management considerations. Too high temperatures pose a threat to sensitive components such as chips and processors but can also affect adjacent structures and thus the functionality of the whole system. Thus the general goal is to design a well-defined heat transfer from these sources into safe regions of lower temperature (sink).

LITERATURE SURVEY

In order to achieve a preferable heat transfer performance one has to gain knowledge on the following aspects:

- Mechanisms of heat transfer within the structure and their crucial design parameters.
- Ways to model and predict the boards heat transfer performance.
- Common techniques for well-defined heat transfer and how to apply them.

All these aspects are examined in many ongoing research projects. This project serves to identify and summarize the crucial points within the fields mentioned above.

PROJECT DESCRIPTION

1. Mechanisms of heat transfer within PCBS and design parameters

In general the three common principles of conduction, radiation and convection all occur within PCBs. The latter two apply directly to the surface mounted components and surface layers of the board. In many cases forced convection e.g. with help of ventilation is not possible as the PCBs are in a sealed environment or as this is not feasible for small/mobile applications. Thus a lot of emphasis is laid on designing for good conductivity. Furthermore are convection and radiation heavily dependent on the board's environment which is often given and not to be altered. The main mechanisms which lies within the PCB-designers scope is thus conductivity which shall be more deeply examined in the following sections.

However, there exist some general design issues which need to be kept in mind and examined with respect to convection and radiation:

- Large heat sources should not be placed in close proximity to sensitive components as they may raise the operating temperature to a critical level. Formulas to determine the critical distance in such cases can be found in [1].
- Convection is a gravity-bound principle which means that there exists a significant difference between whether the PCB is arranged horizontally or vertically.
- When placing several components in a row natural convection flow can create turbulent wakes and increases heat transfer [1].

As mentioned above conduction is the main design parameter with regard to heat management. Figure 1 shows a simple arrangement of a PCB with an isolating layer (light grey, index g) copper layers (index c) and a heat source.

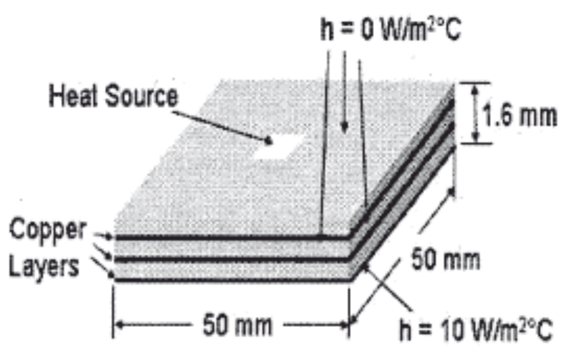

Fig. 1 Simplified model of a PCB

With regard to the conductivity one can apply the following formulas:

$$k_{p,e} = \frac{\sum_{i=1}^{N_c} k_c t_{c,i} + \sum_{i=1}^{N_g} k_g t_{g,i}}{t}$$

$$k_{n,e} = \frac{t}{\sum_{i=1}^{N_c} t_{c,i}/k_c + \sum_{i=1}^{N_g} t_{g,i}/k_g}$$

Note the crucial difference between parallel (p) and normal (n) conductivity. This can be explained by a serial arrangement of thermal resistances in case of the normal orientation and parallel arrangement in the parallel direction. The actual (local) values may very due e.g. drillings, the fact that the copper layers are actually patterns and not one complete area, adhesives between the layers or the influence of surface mounted components. As a general rule due to the planar structure of the boards a ratio of at least 25:1 parallel to normal is suggested to be assumed [3]. From the formulas above it is obvious that critical design parameters with regard to conductivity are material choice as well as layer thickness.

When introducing more sophisticated ways to calculate the effective conductivity of a board more factors come into play however (consider [3] for further elaborations):

- Spreading resitances where open space occurs in e.g. wire pattern-board material stack can have a significant influenece.
- The source size needs to be considered.
- The position of the source has an effect in terms of proximity to heat sinks or adiabatic sections of the board.

2. Modelling PCBs for examining heat management characteristics

As it directly connects to improving algorithms for thermal simulations the modeling of PCBs is of vital interest in ongoing research. Generally there exists a conflict of interests between the precision of the model and the needed computational power to calculate and simulate it. Also in many cases it is unfeasible to digitally construct the exact wire patterns, drillings, applied adhesives etc. to achieve an accurate model. Where rough calculations suffice the board can be modeled as a solid block with the average efficient conductivity as arithmetic mean of the parallel and normal conductivity [3]:

$$k_{e,avg} = \frac{k_P + k_n}{2}$$

When aiming for more precise results nonisotropic conductivities, source size, spreading resistance etc. should be included in the model. Common simplifications are to model the sides of the boards as adiabatic (if not conductively connected to a cold wall) while top and bottom surface are exposed to defined convective boundary conditions. A common value for the Biot number is e.g. in the range of 0.01 to 10. With regard to the heat source separate modeling schemes can be applied. It is important to consider radiative heat transfer in this case. The simulations are often carried out with FEM or CFD software or combinations of both.

3. Solutions and Applications for heat management in PCBs

As indicated in section 1 the choice of materials plays a major role in defining the boards conductivity. However, compromises need to be made as the material choice also needs to fulfill requirements regarding density, stiffness and Joule heating. The ideal material would be furthermore characterized by a low CTE (coefficient of thermal expansion), high T_g (glass transition temperature), low dielectric constant, and non-brittle resins. They should also be easy to drill, plate, bond and be cheap [2]. The following tables show an overview over typical board materials and other materials within PCB structures.

Material	Tg (°C)	CTE $(10^{-6}/K)$	Thermal Cond. (w/mK)	Density (g/cc)
Epoxy	125	14	0.36	1.8
Modified Epoxy	150/180	14	0.36	1.8
BT Epoxy	180/200	14	0.36	1.8
Polyimide	200–280	13	0.36	1.8
Copper		17	394	8.9
Aluminiym		23.5	239	2.7
Alumina		7.2	33	3.9

Material	Tg (°C)	CTE $(10^{-6}/K)$	Thermal Cond. (w/mK)	Density (g/cc)
Cyanate Ester	240	12	0.36	
Copper/Invar Copper 20/60/20		7	172/24	8.5
Copper/ Molybdenum/ Copper 13/74/13		8	218/167	9.9
Carbon Fibre	240	−2	600	2.2
Invar		0.9	16	8.0
Molybdenum		5.1	137	10.2
Kevlar		−2		

Figure 2 Materials found in PCB structures [2]

Note the 1000 times higher conductivity of copper compared to epoxy materials. It is also worth noting, that carbon fibre unites a favourable conductivity with higher stiffness than copper and lower density. This can be of interested when installing layers dedicated to thermal management (see following section).
With regard to the board design it has been mentioned that several layers with wire patterns can be stacked. The connection between two surface components is than made through dedicated plated drillings from the surface to these layers. Similarly can such drillings connect the components to layers of high thermal conductivity. Such layers can directly lead into a cold wall and thus speed up the heat transfer away from the sources. This principle is illustrated in figure 3.

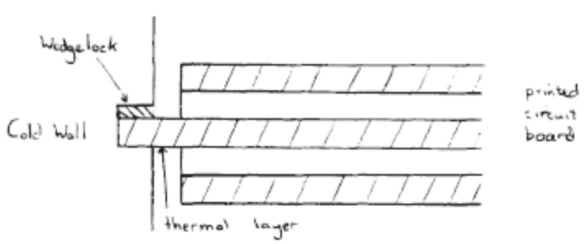

Figure 3 principle of a thermal layer leading into a cold wall [2].

The drillings take a special shape and are referred to as thermal vias which can also lead to the opposite side of the board instead of connecting to a thermal layer. Figure 4 shows such a via located under a thermally sensitive chip. It is obvious that in this case special attention needs to be payed to forming a proper contact between chip and via as airgaps can decisively limit the heat transfer. This problem can be solved by applying dedicated thermal pads which are inserted into the drilling.

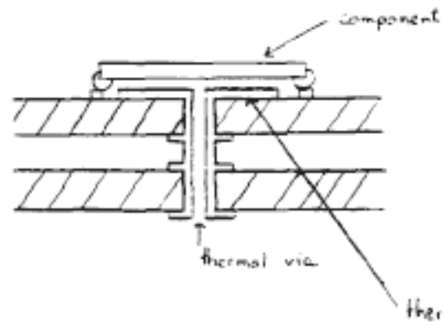

Figure 4 Application scenario of a thermal via and pad to cool an surface mounted component

Finally if it cannot be avoided forced convection can also be applied. As an alternative to the known application of a fan also a build-in PCB ventilation system can be found. This principle is illustrated below.

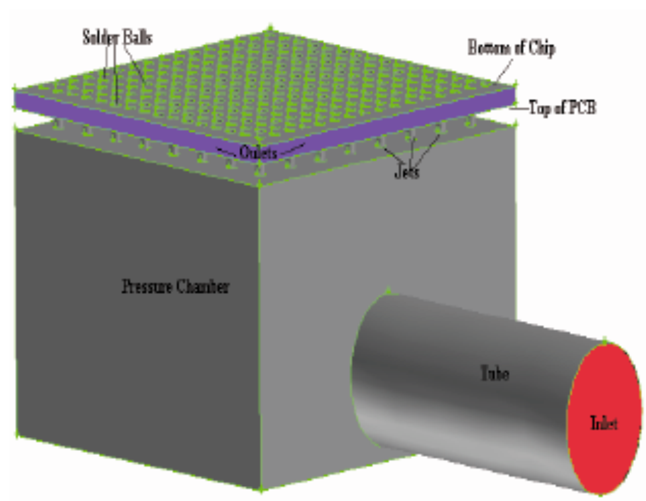

Figure 5 Principle of a jet cooled chip with an internal ventilation system inside the PCB.

CONCLUSIONS

It has been shown that heat management in PCBs is an increasingly important aspect when designing electronic applications. The basic heat transfer mechanisms have been identified and analyzed with respect to their crucial design parameters. Simple ways to determine the board's conductivity have been introduced and steps described to achieve more precise calculations and models. Finally common techniques to achieve feasible heat transfer characteristics have been discuseed.

REFERENCES

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[3] Culham, J.R. and Yovanovich, M.M., 1998, “Factors affecting the calculation of the effective conductivity in printed circuit boards”, 1998 InterSociety Conference on Thermal Phenomena (nor further source information available)