Experimental Investigation of Temperature-Current Rise in Fine PCB Copper Traces on Polyimide, Aluminium and Ceramic (Al$_2$O$_3$) Substrates

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Abstract. Three types of copper traces for PCBs were investigated: 1) 2.5 µm thin film lines (Ti;Cu;Ni) on aluminium and ceramic (Al$_2$O$_3$) substrates; 2) 2.5 µm thin film lines (Ti;Cu;Ni;Au) on ceramic (Al$_2$O$_3$) substrates; 3) 15 µm traces (Cu;Ni) on polyimide substrate for high density interconnection PCBs. The width of all types of traces was varying in the range of 100-500 µm. The set of temperature-current diagrams for different PCB scenarios are presented and analyzed. The temperature caused by Joule heating was measured using IR camera Flir A40 with macro lens. For different cases the current was set in the range of 0.1-3 A; the measured temperature was in the range of 20-140 °C. The close agreement between the results measured and simulated with ELCUT software tool was achieved.

Introduction

The increasing demands for miniaturization and better functionality of electronic components and devices have a significant effect on the requirements facing the printed circuit board (PCB) industry. PCB manufactures are driving for producing high density interconnect (HDI) boards at significantly reduced cost and reduced implementation time. The interconnection complexity of the PCB is still growing and today calls for 50/50 µm or 25/25 µm technology are real.

The wide requirements for higher power density in many power electronic applications, such as telecommunication and automobile, causes the current density in PCB traces increase constantly. How much current PCB traces are able to carry is a question that most of PCB designers concern about. Therefore, sizing PCB traces for a certain amount of temperature rise with applied currents is normally the first step of the PCB thermal management. The current carrying capacity (CCC) of PCB traces is the maximum current that can be applied in PCB traces to achieve maximum allowable temperature rises in traces.

When current is applied to a conductor, its temperature rise is dependent upon its cross sectional area and factors such as the PB thickness, PB material, amount and adjacency of copper in the PB, and the environment in which PB is being operated. The mounting of the PB, environment (air, vacuum, forced air), copper plane layers, the components that the conductor is connected to, and length of the conductor are partial list of the things that can impact the conductor temperature rise.

In previous works the problem of PCB CCC was investigated. In work [1] the traces with conductor thickness from 35 µm to 120 µm, width from 125 µm to 500 µm, board thickness from 0.78 mm to 1.6 mm were investigated. But the temperature rise was limited up to 50 °C. In standard IPC-2152 [2] the trace temperature rise exclusively depends on the conductor cross section area but the influence of varied trace length is neglected. Brooks [3] introduced separate dependence on trace width and thickness in his CCC equation by curve fitting techniques. Adam [4] expanded CCC charts of more board scenarios based on the verified mathematical model. In experimental work [5] the current carrying capability of FR-4 PCBs for high load currents was measured. In [6] the influence of a distance from trace edge to board edge and corner effect of FR-4 PCBs was investigated. In [7] the thermal coupling of parallel tracks of FR-4 PCBs was analyzed.
The results presented in mentioned above works are developed on PCBs with large sizes (thick base materials and large spacing between traces). Moreover, these results were received for traces with width more than 200 µm, thickness more than 18 µm and did not included CCC dependence on trace length. The traces on Al substrate and multi-layer traces (Ti;Cu;Ni) were not investigated. So they cannot reliably predict the trace CCC of modern PCBs.

The purpose of this work is experimental CCC investigation for modern PCB traces taking into account the factors mentioned above.

**Traces on Polyimide Substrate**

This base material is used for flexible PCB production. In this work we investigate the CCC for fine traces of modern PCBs. In previous work [4] the CCC for traces with conventional sizes: substrate thickness 300 µm, trace width ≥ 200 µm, trace thickness 35 µm were investigated. In our work we investigated the CCC fine traces for HDI PCB technology.

A board with several test structures was designed. The copper tracks with width (100 and 175 µm), and length (10, 30, 60, 120 mm) were studied. The base material is polyimide, board thickness is 24 µm, board sizes are 150x120 mm, trace thickness is 15 µm (12 µm Cu and 3 µm Ni). In Fig.1. the fragment of the trace with pad on polyimide substrate is presented. Ambient condition is “still air” (i.e. free convection) with $T_a=20 \, ^\circ C$.

Two types of experiments were developed: 1) CCC dependence on track width (100 and 175 µm) and T-I characteristics for two parallel tracks with w=175 µm and 200 µm spacing, the length of all traces is 60 mm (Fig. 2). 2) CCC dependence on trace length l (10, 30, 60, 120 mm), trace width is w=100 µm (Fig. 3).

![Fig. 1. Fragment of the trace with pad on polyimide substrate.](image)

![Fig. 2. Mean temperature of a trace as function of electrical current for different trace widths.](image)

![Fig. 3. Mean temperature of a trace as function of electrical current for different trace lengths.](image)

It is seen in Fig. 2 that the critical temperature is growing with trace width decrease. The cross sections were obtained: 0.0012 mm² and 0.0021 mm². While the smallest cross section cannot carry more than 0.31 A, a two times larger cross section can carry up to approximately 0.5 A before reaching the same temperature.
In addition the mutual thermal influence of two parallel tracks was investigated. The temperature values measured in the middle of these traces are given in Fig. 2. It is seen that in case of two parallel tracks the T(I) curve is raised two time faster than for single track.

It is seen in Fig. 3 that length of the trace has considerable impact on CCC with small lengths (30-10 mm), while for great values of length (more than 30 mm) of the trace its influence doesn't exceed 15-20%.

**Traces on Aluminium Substrate**

Insulated metal substrate (IMS) consists of a metal baseplate (aluminium) covered by a thin layer of dielectric (polyimide) and a layer of copper. The aluminium substrates are specially used in PCBs where the very high temperature conductivity is necessary. Also this base material can be used for rigid-flex PCB production. The authors are not familiar with publications where experimental results for thin film traces on Al-substrate were presented.

The test PCB was manufactured in two versions with nominal aluminium thicknesses of 240 µm and 800 µm. Polyimide thickness is 4 µm. Metallization thickness Ti/Cu/Ni is 0.05/2/0.45 µm. The trace width is 150 µm and the lengths of the conductors are 8, 13 and 27.5 mm. Board sizes: 60x48 mm (see Fig. 4). Two types of experiments were developed: 1) CCC dependence on substrate thickness; 2) CCC dependence on trace length l.

In Fig. 5 the dependencies between measured temperature and load current for all trace lengths and substrate thickness are shown. The temperatures of the corresponding structures for a given current are higher for the 240 µm PCB than in case of the 800 µm board due to the worth heat spreading. The working temperature of traces on 800 µm substrate is 50% more than on the 240 µm thick substrate.

Comparing the results for traces with different length in Fig. 5 the weakest current carrying track is the 27.5 mm trace length. It is seen in Fig. 6 that for both of substrates the temperature is growing in two times with increasing of length of a payment from 8 mm to 27.5 mm.

![Fig. 4. Fragment of the studied trace with pad on aluminium substrate](image)

![Fig. 5. Mean temperature of a trace as function of electrical current for different PCB scenarios](image)

![Fig. 6. IR image of the tracks on the 240 µm thick substrate at 1.2 A](image)
Traces on Ceramic (Al\(_2\)O\(_3\)) Substrate

The ceramic substrates are used in PCBs for microwave applications where minimal substrate electrical conductivity is necessary.

In previous work [4] the CCC for Cu traces on Al\(_2\)O\(_3\) substrate with conventional sizes: substrate thickness 0.5 - 1 mm, trace width \(\geq 200\) µm, trace thickness 35 µm were investigated. In our work we investigated the fine traces for state of the art PCB technologies.

The test board was manufactured on the base of Al\(_2\)O\(_3\) substrate with nominal thickness of 500 µm. Board sizes: 60x48 mm.

Two sets of traces are developed: 1) Ti/Cu/Ni (0.05/2.0/0.45 µm), the trace width is 100 µm with different lengths 40 mm and 10 mm. 2) Ti/Cu/Ni/Au (0.05/2.0/0.3/0.05 µm) the trace length is 10 mm with different widths 150 µm, 300 µm, 530 µm (see Fig. 7).

The experimental CCC functions are presented in Fig. 8 and Fig. 9.

It is seen in Fig. 8 that the temperature is growing in two times with increasing of length payment from 10 mm to 40 mm. These results are in good agreement with the results of our experiment with aluminium substrates, (see Fig. 4).

It is seen in Fig. 9 that the width of the trace has a great impact on CCC and that at increase in width of the conductor twice working temperature decreases approximately by 40%.

Electro-Thermal Analysis with ELCUT CAD

The experimental results presented above were compared with simulation results received by electro-thermal FEA (Finite Element Analysis) software tool ELCUT CAD [8].

For example, simulation results for a 100 µm Ti/Cu/Ni (0.05/2.0/0.45 µm) track at 0.68 A placed on Al\(_2\)O\(_3\) substrate are presented in Fig. 10. The maximal trace temperature is 396 K (123 °C). For comparison, the measured temperature for this trace is 120 °C (see point A in Fig. 8).
For all the cases of tracks investigated in this work the good agreement between simulated and measured results was achieved.

Summarizing the results in Fig. 11 we see the good agreement between simulated and measured results.

![Fig. 10. Temperature distribution in the track at I=0.68 A.](image)

![Fig. 11. Comparison of measured and simulated results.](image)
Conclusions
Experimental Temperature-Current characteristics for new generation of fine PCB copper traces on polyimide, aluminium and ceramic (Al$_2$O$_3$) substrates are presented.

The T-I diagrams for 2.5 µm multilayer (Ti;Cu;Ni) thin films on aluminium and ceramic (Al$_2$O$_3$) substrates; 2.5 µm (Ti;Cu;Ni;Au) thin films on ceramic (Al$_2$O$_3$) substrate and 15 µm traces (Cu;Ni) on polyimide substrate with different sizes (width, thickness, length) were investigated. The current was varying in the range of 0.1-3 A; the temperature - in the range of 20-140 °C. The local temperatures and 2D temperature distributions were measured using IR camera FLIR A40 with macrolens.

ELCUT software tool was used for temperature distribution modeling in different types of PCB traces. The good agreement between simulated and measured results was obtained. The modeling error is about 10-15%.

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References