INVESTIGATION OF THE EFFECTIVE THERMAL CONDUCTIVITY OF PCB

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The investigation deals with the numerical solution of the 3D heat conduction equatioin and study variation of the effective conductivity of PCB with different component size. Cases with and without a copper layer on the component side and different PCB thicknesses were investigated. It was shown that the effective thermal conductivity of a PCB with/without a copper layer on the component side would be larger/smaller than the values given by the one-dimensional effective thermal conductivity model if the components mounted on the PCB were smaller than the PCB itself. The difference was more pronounced for smaller components. Correlations were obtained for the effective thermal conductivity of PCBs.

Keywords: PCB, CFD, Thermal conductivity

1. INTRODUCTION

The amount of heat that is dissipated through the printed circuit board (PCB) becomes an important fraction of the total heat dissipated by microelectronic devices due to the increase in power density and the reduction in space available for heat sinking them [1]. This is especially important for SO and SOT surface mount plastic packages including GaAs FET amplifiers and RF transistors, and through-hole or surface mount TO packages including miniature voltage regulators [2]. The heat generated in these devices is transferred through their leads or cases to the PCB. Because of the large difference between the thermal conductivities of copper and glass-epoxy, the thermal conductivity of the PCB, as a whole, is strongly anisotropic. Detailed representation of the individual layers of PCBs in a thermal-fluid model of an electronic system makes the model too big, and the solution process too slow.

It was shown that the placement of the various layers, source size and placement, and the convective boundary conditions have significant effects on the effective thermal conductivity of a PCB [3].

Although there have been many studies on the effective thermal conductivity of a homogeneous model of a PCB, similar studies on the anisotropic model of a PCB, to the knowledge of the author, are lacking. On the other hand, as the component size decreases, the conduction through the board becomes a complex two or even three-dimensional phenomenon. In this paper is shown how inaccurate the 1D model can be in such situations.

Effects of the component size on the parallel and normal effective thermal conductivities of a PCB will be studied.

2. MODELLING

PCBs are usually modeled as single objects with parallel (in the plane of the board) and normal (perpendicular to the board) effective thermal conductivities. The effective parallel and normal thermal conductivities, $k_{p,e}$ and $k_{n,e}$, are typically calculated assuming one-dimensional heat conduction through a composite layer [4], and neglecting the thermal contact resistance between the copper and glass-epoxy layers [5]. For a PCB with N_c number of copper layers and N_g number of glass-epoxy layers

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

$$k_{n.e} = \frac{t}{\sum_{i=1}^{N_c} t_{c,i} / k_c + \sum_{i=1}^{N_g} t_{g,i} / k_g} \qquad (2)$$

where t is the total thickness of PCB, $t_{c,i}$ and $t_{g,i}$ are the thicknesses of the ith copper and glass-epoxy layers, and k_c and k_g are thermal conductivities of copper and glass-epoxy. This model here is called the "one-dimensional effective thermal conductivity" model (1DM).

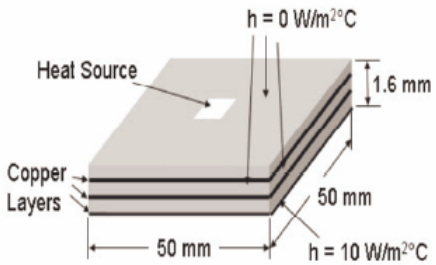

Fig.1: Printed circuit board with two internal copper layers and a copper layer on the solder side.

Consider a 50 mm x 50 mm x 1.6 mm PCB with two (35 μm thick) internal copper layers and a copper layer on the solder (bottom) side (17 μm thick) as shown in Fig. 1. The internal copper layers are positioned uniformly in the PCB thickness. The top and sides of this PCB are insulated and the convection heat transfer coefficient and air temperature on the bottom side are 10 W/m^0C and 20^0C. The toplayer of this PCB, on which the components are mounted, is a glass-epoxy layer. Since the thermal conductivity of glass-epoxy is very low, this layer creates a large conduction thermal resistance against the heat flow into and through the PCB. Fig. 2(a) shows the computed temperature contours in this PCB with a 5 mm x 5 mm heat source centrally located on it. The heat

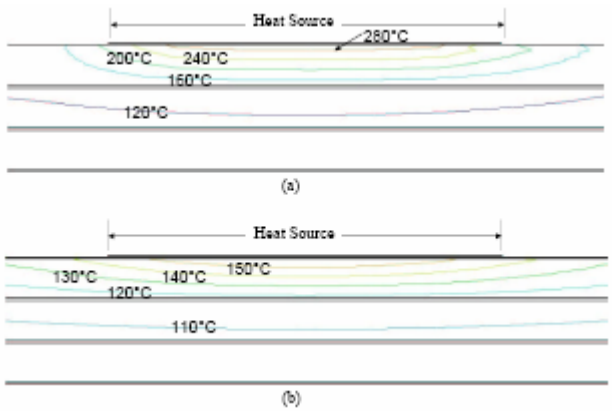

Fig.2 Temperature contours in a 1.6 mm thick PCB with two internal copper layers; (a) no copper layer on top surface (b) copper layer on top surface.

source dissipates 2 *W*. A large temperature gradient is seen near the heat source as a result of high conduction resistance. If the thermal conductivities of copper and glass-epoxy are 390 W/m^0C and 0,25 W/m^0C respectively, Eqs. 1 and 2 give the parallel and normal thermal conductivities $k_{p,e}$ = 21,56 W/m^0C and $k_{n,e}$ = 0,264 W/m^0C for the 1DM model of this PCB. It is seen that the parallel thermal conductivity of the PCB is too high compared to the thermal conductivity of glass-epoxy.

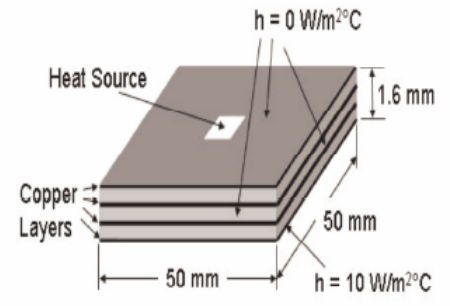

Fig. 3 Printed circuit board with two internal copper layers, a copper layer on the component side and a copper layer on the solder side.

There are also situations in which the component (top) side of a PCB, or at least part of it, is covered with a layer of copper. This copper layer helps to spread the heat over a larger area. Fig. 2(b) shows the computed temperature contours in a 50 *mm* x 50 *mm* x 1,6 *mm* PCB with two internal copper layers, a copper layer on the solder side, and a copper layer on the component side. The internal copper layers are positioned uniformly in the PCB thickness. A 5 *mm* x 5 *mm* heat source, dissipating 2 *W*, is centrally located on the component side as shown in Fig.3.

The boundary and ambient conditions are the same as the case with no copper layer on the topside. It is seen that, because of the high thermal conductivity of copper, the top copper layer offers a low resistance path against the heat conduction into the board. Again the 1DM model does not replicate this behavior. The effective parallel and normal thermal conductivities of such a model for this PCB are $k_{p,e}$ = 25,83 W/m^0C and $k_{n,e}$ = 0,268 W/m^0C. It is seen that the parallel thermal conductivity of the PCB model is much smaller than the thermal conductivity of copper.

For given boundary conditions, the maximum heat source temperature, T_s, and the maximum temperature of the board opposite the heat source, T_b, are functions of the PCB length, L_b, and thickness, t, number of copper layers, N_c, thickness of the *i*th copper layer, $t_{c,i}$, number of glassepoxy layers, N_g, thickness of the *i*th glass-epoxy layer, $t_{g,i}$, thermal conductivities of copper and glass-epoxy, k_c and k_g, and the length of the heat source ,L_s.

$$T_s = f_1(L_b;\ t; N_c;\ t_{c,i}; N_g;\ t_{g,i};\ k_c;\ k_g; L_s) \quad (3)$$

$$T_b = f_2(L_b;\ t; N_c;\ t_{c,i}; N_g;\ t_{g,i};\ k_c;\ k_g; L_s) \quad (4)$$

Now let's assume this PCB is modeled as a single object with different parallel and normal thermal conductivities. For the same boundary conditions, the maximum heat source and board temperatures are functions of the PCB length, L_b, and thickness, t, parallel and normal thermal conductivities of the PCB model, k_p and k_n, and the length of the heat source, Ls.

$$T_s = g_1(L_b;\ t;\ k_p;\ k_n;L_s) \quad (5)$$

$$T_b = g_2(L_b;\ t;\ k_p;\ k_n;L_s) \quad (6)$$

Equating Eq. 3 to Eq. 5 and Eq. 4 to Eq. 6 gives two implicit equations for the parallel and normal thermal conductivities of the PCB model. These equations show that the parallel and normal thermal conductivities of the PCB model have to be functions of the number, thickness and thermal conductivity of each copper and glass-epoxy layer as well as the heat source and board dimensions.

$$k_p = h_1(N_c;\ t_{c,i};N_g;\ t_{g,i};\ k_c;\ k_g;\ t;L_b;L_s) \quad (7)$$

$$k_n = h_2(N_c;\ t_{c,i};N_g;\ t_{g,i};\ k_c;\ k_g;\ t;L_b;L_s) \quad (8)$$

The 1DM model neglects the dependence of k_p and k_n on the heat source and the PCB dimensions, L_s and L_b.

3. RESULTS

Numerical solutions of the three-dimensional heat conduction equation for a PCB and a heat source were used to establish correlations for Eqs. 7 and 8. Two different representations of a PCB were simulated with the Computational Fluid Dynamics (CFD) software ANSYS [6]. The first consisted of a square PCB, whose length was between 50 *mm* and 70 *mm*, modeled with details of the copper and glass-epoxy layers. A square shape heat source (5 *mm* x 5 *mm* to 45 *mm* x 45 *mm*) was centrally located on the topside of this PCB. The second model was similar to the first except that a single object with an effective parallel and an effective normal thermal conductivity represented the PCB. It was assumed that the top side of the PCB (the component side) was insulated and a heat transfer coefficient of 10 W/m^0C and ambient temperature of 20^0C were assigned to the bottom side of the PCB. This boundary condition was chosen since, in many practical situations, the topside would be filled with components and there would not be much of the board area left exposed to heat convection. The effective parallel and normal thermal conductivities of the PCB model were obtained by an iterative procedure. This procedure included two steps. First, numerical solution of the heat conduction equation in the detailed PCB geometry was used to obtain the maximum source temperature and the maximum board temperature opposite the source. Then,

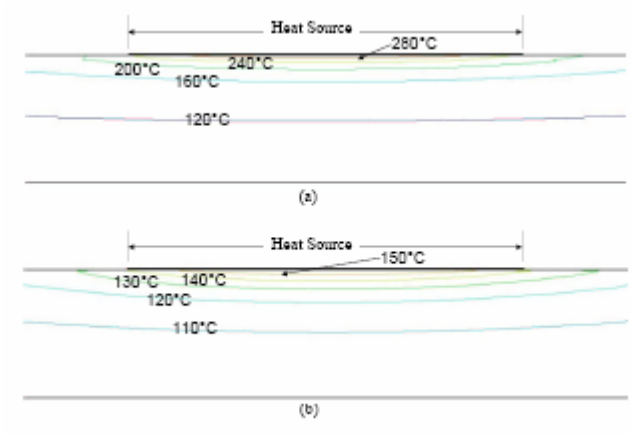

Fig.4: Temperature contours in the MM model of a 1.6 mm thick PCB with two internal copper layers; (a) no copper layer on top surface (b) copper layer on top surface.

numerical solution of the heat conduction equation in the orthotropic model of the same PCB (the second model mentioned above) was obtained with a given set of parallel and normal thermal conductivities. These thermal conductivities were iteratively corrected such that the maximum heat source temperature and the maximum PCB temperature opposite the heat source were predicted within 1% of the values predicted by the detailed PCB simulation. The PCB model that uses these thermal conductivities was called the "modified effective thermal conductivity" model (MM). Two convergence criteria were used for all the numerical solutions; reduction of the residual of the temperature equation below 10^{-12} and less that 0.1% variation in the maximum source temperature in each iteration. Fig. 4 shows the temperature distribution across the PCB model for the MM model. The MM model provides better predictions of the spreading resistance of the top glass-epoxy layer in case (a) and the heat spreading capability of the top copper layer in case (b) compared to the 1DM model.

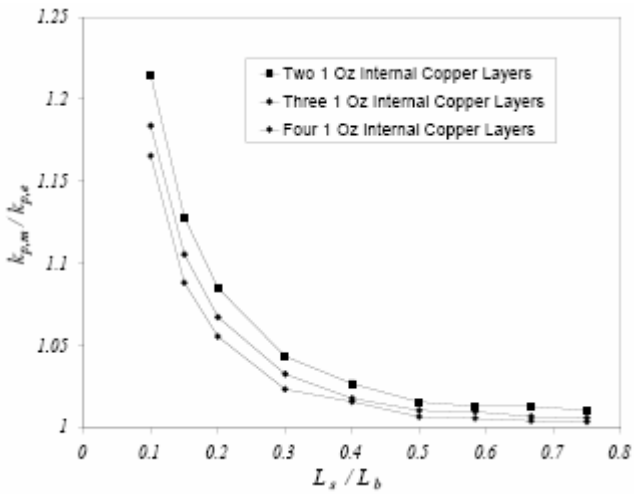

Fig 5 Parallel thermal conductivity of a 2.1 mm thick PCB as a function of the heat source dimension. Topside of PCB is covered with a copper layer.

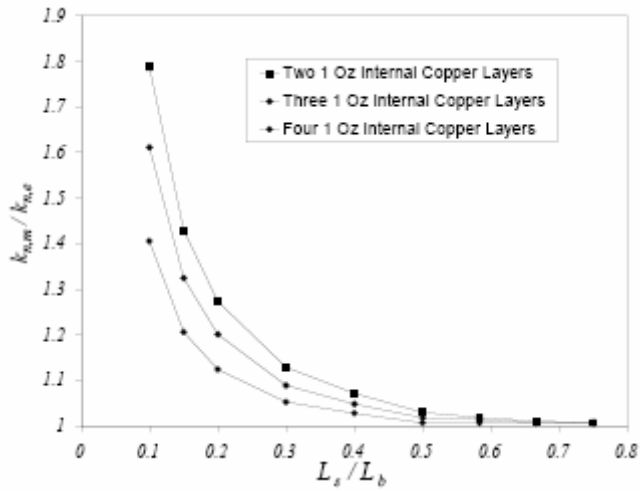

Fig. 6 Normal thermal conductivity of a 2.1 mm thick PCB as a function of the heat source dimension. Topside of PCB is covered with a copper layer.

The above numerical procedure was repeated for different source sizes to find the parallel and normal thermal conductivities for the MM model as a function of the heat source dimension. Figs. 5 and 6 show the ratio of the modified to one-dimensional parallel and normal thermal conductivities, $k_{p,m} = k_{p,e}$ and $k_{n,m} = k_{n,e}$, for a 2,1 *mm* thick PCB, with a copper layer on the top side, as a function of the heat source dimension. It is seen that the ratio is always larger than one. The ratio approaches one as the heat source dimension approaches the PCB dimension or as the number of internal copper layers increases.

It was observed that if $k_{p,m}/k_{p,e}$ and $k_{n,m}/k_{n,e}$ were plotted against a scaled source length defined as $(L_s/L_b)(t_c/t)^{0,5}$, where t_c is the total thickness of all the copper layers, the results for 1,6 *mm* thick PCBs, for various numbers of internal copper layers, would collapse into a single curve (Fig. 7).

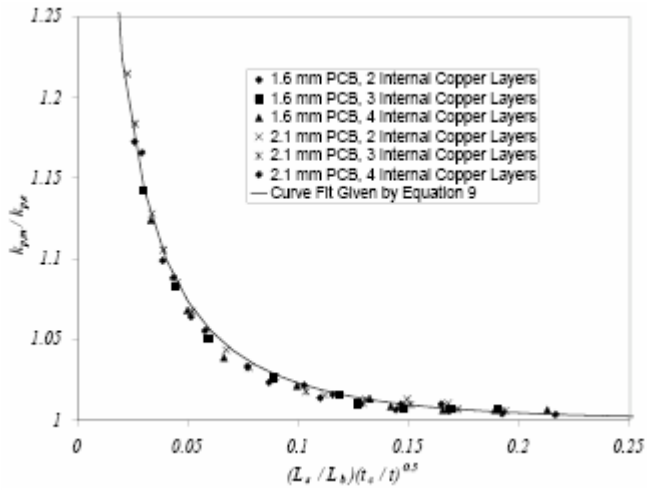

Fig. 7: Variation of parallel thermal conductivity of a PCB. Top side of PCB is covered with a copper layer. All internal copper layers are identical.

Appropriate curve fit correlations for these data are given by Eqs. 9 and 10 for the cases with a half-ounce copper layer on the topside of PCB, and by Eqs. 11 and 12 for the cases with no copper layer on the topside of PCB.

$$k_{p,m}/k_{p,e}=[1-\exp(-12((L_s/L_b)(t_c/t)^{0,5})^{0,5})]^{-1} \quad (9)$$

$$k_{n,m}/k_{n,e}=[1-\exp(-26((L_s/L_b)(t_c/t)^{0,5})^{0,9})]^{-1} \quad (10)$$

$$k_{p,m}/k_{p,e}=1-\exp(-8,6((L_s/L_b)(t_c/t)^{0,5})^{0,6}) \quad (11)$$

$$k_{n,m}/k_{n,e}=1-\exp(-12,8((L_s/L_b)(t_c/t)^{0,5})^{0,9}) \quad (12)$$

It must be mentioned that these equations are accurate for the PCBs studied in this work. More investigations are required to study the effects of the boundary conditions, thickness and spacing of the internal copper layers, source and board shapes, and thickness of the topside copper layer.

4. CONCLUSIONS

It was shown that the effective thermal conductivities of printed circuit boards depend on the component size. Numerical solutions of the heat conduction equation were used to obtain effective thermal conductivities of printed circuit boards with different size components. These thermal conductivities were larger than the values given by the one-dimensional effective thermal conductivity model when the top side of the board was coated with a layer of copper, and smaller than the one-dimensional effective thermal conductivity values when the

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