Thesis for the Degree of Master of Engineering

Thermal Behaviors of Control Modules for Semiconductor Manufacturing Equipment

By

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Thermal Behaviors for Control Modules of Semiconductor Manufacturing Equipment

반도체 제조 장비 제어 모듈의 열 행동

Advisor: Professor Kyoung Joon Kim

by

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Thesis

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Nomenclature

A	area, m^2
b	gap between two fins, m
g	gravitational acceleration, m^2/s
h	heat transfer coefficient, W/m^2K
H	heat sink height, m
k	thermal conductivity, W/mK
L	heat sink length, m
N	number of fins
Nu	Nusselt number
Pr	Prandtl number
q	heat flow rate, W
R	thermal resistance, $^0C/W$
Ra	Rayleigh number
t	Fin thickness, m
T	Temperature, ^0C
W	Heat sink width, m

Greek Symbols

η	Heat sink efficiency
β	coefficient of volume expansion, 1/K
ν	Kinematics viscosity of the fluid m^2/s
μ	Dynamic viscosity, Ns/m^2

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Abstract

Semiconductor fabrication is one of the most complicated process in production industry with more than 700 complex processing steps. It, therefore, requires high-precision and high-speed control of stage for semiconductor manufacturing equipment. The growing of miniaturization and multifunctioning includes the dramatic increase of waste heat density in electronic packages in recent years. Thus, the performance and the reliability of the components, modules, and equipment are being more and more necessary. The issue in electronics thermal management is one of the key factors that affect on the degradation of performance and the reduction of component and module reliability. Consequently, the proper thermal management solution of control modules is required for accurate operation and acceptable reliability.

There are a variety of cooling techniques ranging from the simplest and having lowest cost as natural convection air cooling to the more complicated such as phase change, thermoelectric, microjet cooling, and microchannel heat sink. Based on the complexity and the requirement of an electronic system, an appropriate thermal management solution is selected. The need of accurate thermal characteristic prediction is no exception. Due to the requirements of

time and accuracy, simplicity and high precision are two achievements of the desirable approach.

The research summarized in this thesis describes the possible solution for thermal management of electronic control modules of semiconductor manufacturing. The proposed thermal packaging is established by the combination of thermal interface materials (TIMs) and Copper heat slugs. The improvement of the control modules is also tightly constrained by the mechanical structure design adjustment. The following tasks were done to demonstrate the effectiveness of supposed given solutions. Firstly, the computational investigation was conducted with different conditions including natural convection, and forced convection for the initial modules design and the improved designs. The commercial CFD package ANSYS Icepak was employed to predict the temperature fields of control modules. Secondly, the theory of thermal resistance network analysis was conducted to confirm the results archived by numerical modeling. The thermal resistance model was stimulated in the similar condition to the computational simulation for the robust analysis. In addition, the parametric studies including effects of heat sink structural designs, air flow velocities, thermal interface material properties, and designs of PCB thermal vias were conducted in order to achieve the optimized thermal management solution for electronic control modules.

The obtained thermal performances from numerical analysis and thermal resistance network modeling show that thermal packaging solution is a promising thermal management method for electronic control modules of semiconductor manufacturing. With the considerable reduction of the major components temperature, the random failures of control performances related to thermal issues may mitigate and the reliabilities of components, packages as well as modules will be improved.

Chapter 1

INTRODUCTION

1.1 Outline of the Problem

The miniaturization and multifunction trend of electronic packaging, which has been identified following Moore's law [1], requires the robust and high accurate processing during mass production. For the guarantee of both quality and quantity of production, the requirements of high precision control are needed. Therefore, the control part which includes control modules should not be overload and/or having any failures such as electrical failures, mechanism failures and thermal failures. The failure rate due to thermal problems accounts for the great percentage compared with the other failures according to a survey by the U.S Air Force [2].

1.2 Thermal Management Issue

The operation of the control modules on the semiconductor manufacturing equipment results in the generation of heat. This unwanted issue may lead to serious overheating problem and sometimes can cause a variety of failures of the system. The heat generated within the system must be efficiently removed in order to maintain the accurate operation as well as the reliability of the system.

Thermal management of electronic applications in different level including packages and system has identified and played one of the most important roles in electronic industrial manufacturing. There are variety of strategies for thermal management for electronic systems [3], ranking from air cooling natural convection which is considered as the simplest and has lowest cost as well to the more sophisticated techniques such as immersion cooling or thermoelectric cooling and phrase change system. They have their own advantages and disadvantages, therefore, based on the system requirement, the most appropriate solution will be selected.

To archive the desirable operation temperature, with less complexity of thermal design, the optimal of structure for thermal improvement based on the initial designs should be developed. The numerical investigation related to the thermal performances of control modules with different structures were reported in this study. Besides, the models of thermal resistance network was also analyzed in order to confirm simulation results for robust analysis. In Chapter 2, the explanation of the control modules for semiconductor manufacturing equipment is described in details and the description of thermal packaging solution for electronic cooling. In Chapter 3, the thermal resistance network models are analyzed. The numerical investigation for verifying results from thermal network are presented and discussed in Chapter 4. In Chapter 5, several studies on effectiveness of parameters on thermal performances of control modules were investigated in order to obtain the optimized solution. The conclusions are given in Chapter 6.

Chapter 2

CONTROL MODULES FOR SEMICONDUCTOR MANUFACTURING AND THERMAL IMPROVEMENT SOLUTIONS

2.1 Overviews

Semiconductor fabrication involves one of the most complicated manufacturing process. The fabrication process of semiconductor production may requires more than 700 steps which are done by a series of dedicate and expensive machines [4]. To ensure stable process and meet the strict requirements on final product quality, the high precision of control systems must be established. Control modules are considered as the most important parts of typical control systems. Therefore, the requirements of maintenance for every electronic component as well as the whole module are strongly recommended.

The following figures show the structure of actual control modules for semiconductor manufacturing equipment.

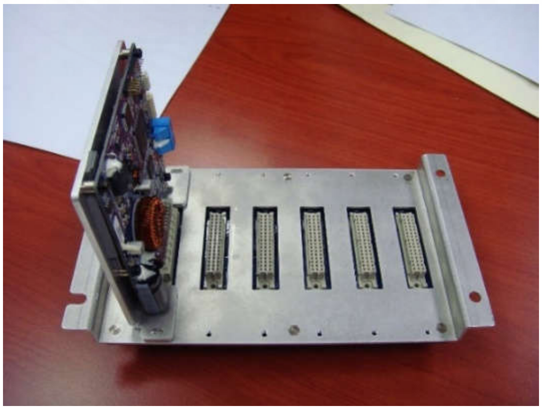


Figure 2.1 The control module TYPE I

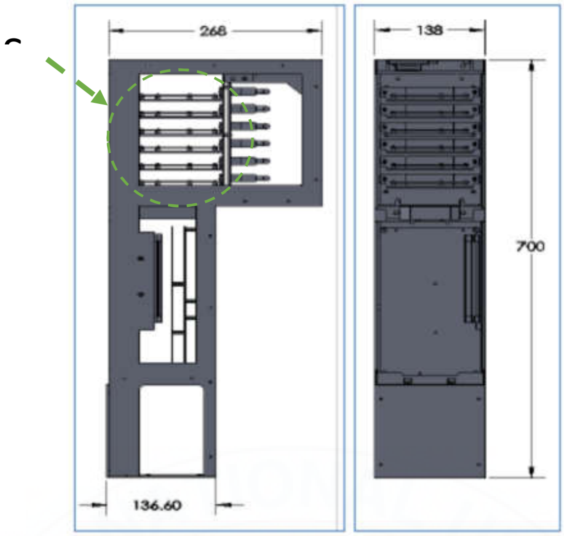


Figure 2.2 The control module TYPE I in the system structure

Figure 2.3 The control module TYPE II

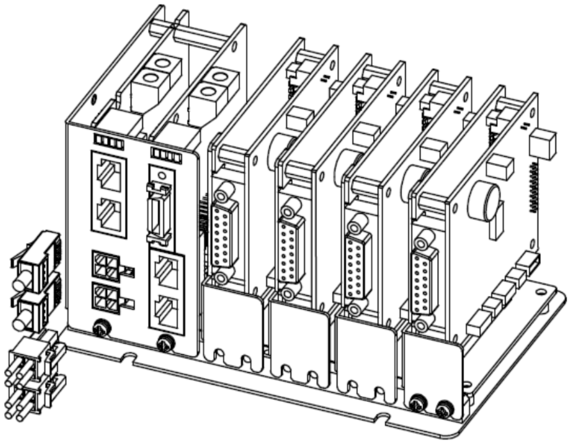


Figure 2.4 The control module TYPE II in the system structure

As clearly seen on Figure 2.1, with the control module TYPE I, there are many electronic components mounted on the printed circuit board (PCB) on both sides including high power diodes, high power transistors, integrated circuits (ICs), controllers, resistors, capacitor and so on… with different heat dissipations. It can be seen that a similar size of aluminum heat spreader attached to the back side of PCB with thermal interface materials connect to the high power components. Then, the series of five similar modules are hanged on a cabinet as shown in Figure 2.2.

Figure 2.3 indicates the structure of several control modules that will be connected to the TYPE I control modules in order to carry out process tasks. Similar to TYPE I, hundreds of electronic components are mounted on a single or double side PCBs and those PCBs will be inserted to aluminum cases which only has the purpose of preservation. As can be seen that there are a variety of small holes located on rear side of the aluminum case for the airflow stream pass through to bring a part of heat generated during the operation.

2.2 Thermal Improvement Solutions

The great importance of thermal management for electronic systems and packages has been recognized for a long time and many advanced thermal management technologies are enable to be the strong candidates for the next electronic systems. The power dissipation per device tends to continue increasing for most electronic packages or systems and at the same time, similar size but the integration and miniaturization of microsystems result in high heat flux density. Therefore, the thermal management solutions are considered as one of the most crucial researches and development areas for electronic manufacturing in general.

There are variety of strategies for thermal improvement of electronic packages and systems, from the simplest solution as air natural convection cooling with air to advanced cooling techniques such as immersion cooling, phase change systems and thermoelectric. Every approach has its own advantages and disadvantages and based on the operation conditions, system designs, average cost and other considerations.

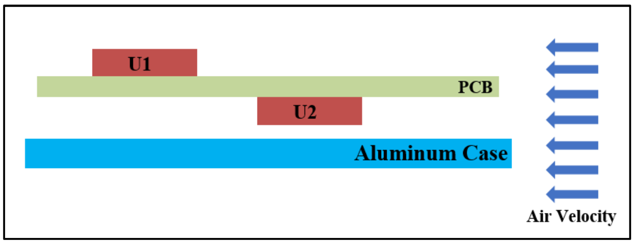


Figure 2.5 The illustration of original design

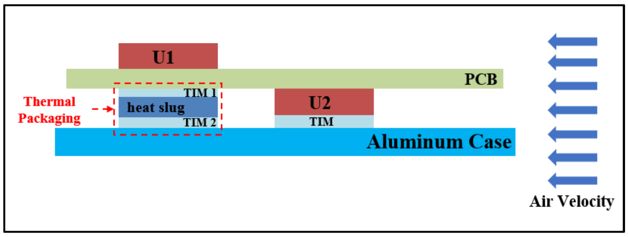


Figure 2.6 The illustration of design with Thermal Packaging Solution

Because of the critical role on the semiconductor manufacturing equipment, the control modules must be well-protected from any risk such as: thermal careless, mechanical and electrical problems. As shown in previous part, the control modules with variety of electronic components including high power devices and sensitive electronic components should not be left in over heat condition. There are two types of structure of the aforementioned control modules as described on section 2.1. Based on the mechanical structure and operation requirements of the machine, air cooling by natural and forced convection were investigation and the idea of creating the thermal packaging was implemented for better results of thermal improvement solutions as shown in Figure 2.5 and Figure 2.6.

Chapter 3

THERMAL RESISTANT NETWORK MODELS FOR CONTROL MODULES

3.1 Problem Statement

Due to the limitation of space and harsh environment of working condition, the thermal analysis is one of great importance in system design in control modules for semiconductor manufacturing equipment. Prediction or determination of the junction temperature of the major and/or sensitive electronic components is necessary for selecting the appropriate thermal management solutions. Several methods are usually employed to carry out this task, including numerical analysis, experiment investigation and thermal network analysis modeling. Study for the methodology which accurate and simple is challenge. Each study methodology has advantages and disadvantages. For instance, the numerical analysis is the most popular method because of its convenient and time consumption saving. Thermal network model [5] is considered as the simplest, time saving and inexpensive as well. However, the requirement of accuracy always ask for robust analysis, therefore, it is necessary to find the approximate model for accurate evaluation the operating temperatures of electronic parts which is sensitive to temperature at the component, package, board, and system level. In this chapter, the thermal resistance network for different types of control modules were developed in order to predict operating temperature of the initial designs as well as the designs with the thermal improvement solution described in Chapter 2.

3.2 Summary of Assumption

This section indicates the assumption used to model the thermal heat flow path in each type of control modules, as follow:

- Steady state, laminar flow;

- One dimensional flow and heat transfer;

- Low heat dissipation components are ignored;

- Aluminum as the heat sink / heat spreader material;

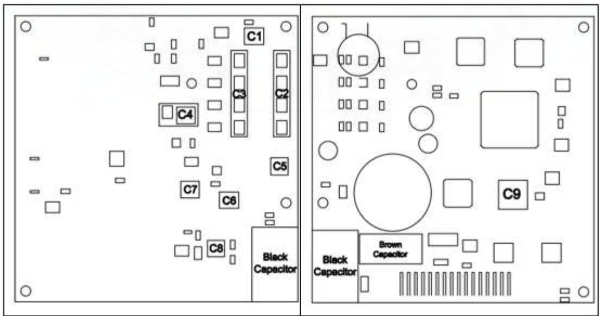
- Thermal packaging contains Thermal Interface Materials (TIMs) and Heat Slug (Copper);

- Air as the fluid.

The obtained results from thermal resistance network analysis will be verified by the numerical investigation data in next chapter.

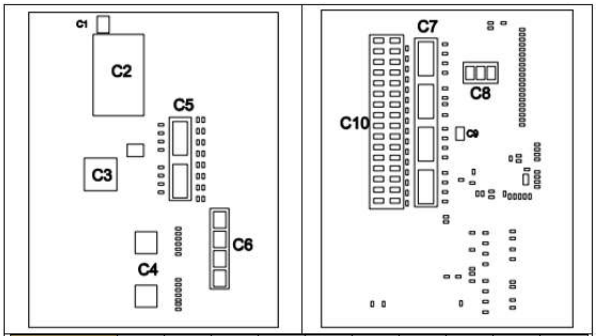
3.3 Thermal Network Models

3.3.1 Physical Design Structures



Components	C1	C2	C3	C4	C5	C6	C7	C8	C9
Power (W)	0.85	1.60	1.60	1.10	0.30	0.49	0.85	1.00	0.22

Figure 3.1 The major heat sources lay out and heat dissipations of control module TYPE I



Components	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
Power (W)	0.09	0.70	0.08	0.12	0.08	0.22	0.10	0.30	0.10	0.48

Figure 3.2 The major heat sources lay out and heat dissipations of control module TYPE II

3.3.2 Thermal Network Model for Control Module Type I

As the previous section mentioned the assumption of our study on thermal resistant network models, we only consider the major heat sources and the temperature sensitive electronic components. The following figures show the thermal resistance network for initial designs of the control modules.

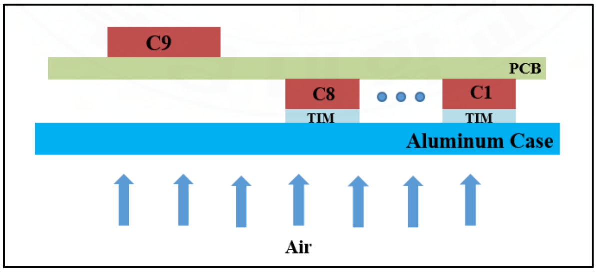


Figure 3.3 – The illustration of model with major components

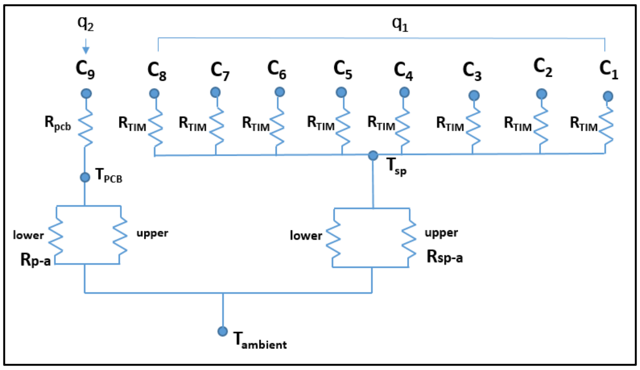


Figure 3.4 – Thermal network for initial design of control module type I

As shown in Figure 3.1 and Figure 3.3, there are nine major components which have high power dissipations involved in the model (marked C_1 to C_9). Figure 3.3 clearly shows that the components C_1 to C_8 are placed in lower side of the PCB and connected to the aluminum case by the regular thermal interface materials (TIMs) as the thermal bridges. Heat generated during the operation is dissipated by the air on two sides of both printed circuit board (PCB) and the aluminum case.

Figure 3.4 indicates the thermal resistance network for the control module type I. As can be seen from Figure 3.4, the heat generated from each component attached to the lower side will be transferred to the aluminum heat spreader and dissipated to the ambient by natural convection. For the device that placed on upper side of the PCB, the heat dissipated through the PCB and expanded to the upper surface of PCB. Finally, heat will be distributed to the surrounding by natural convection on both sides of PCB.

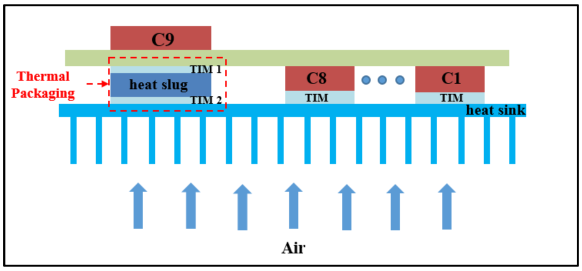


Figure 3.5 The illustration of thermal improved design

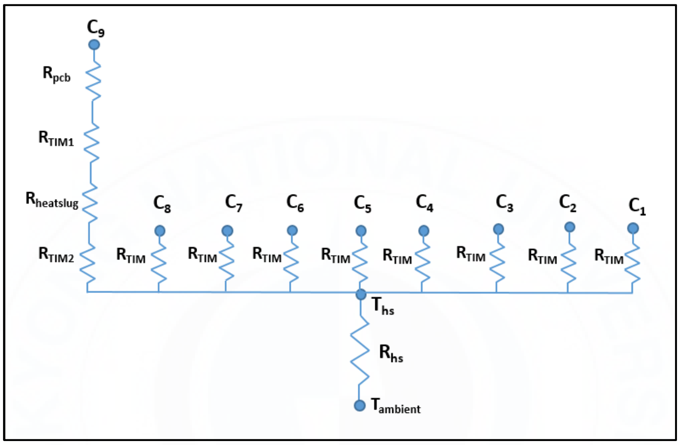


Figure 3.6 – Thermal network for improved design of control module type I

The idea of creating the right thermal heat path for the high heat density components by using thermal packaging as described in the previous chapter and applying the better TIMs with high thermal conductivity. For more efficiency, the aluminum heat sink with reasonable fin height is applied instead of the heat spreader of the original design. Figure 3.6 shows the thermal resistance network model for improved design with thermal improvement solution added. The power dissipated from major heat sources will be carried to the heat sink through “thermal packaging” and TIMs, then, being distributed to the ambience by natural convection.

3.3.3 Thermal Network Model for Control Module Type II

Similarly, the control module type II is being analyzed as following.

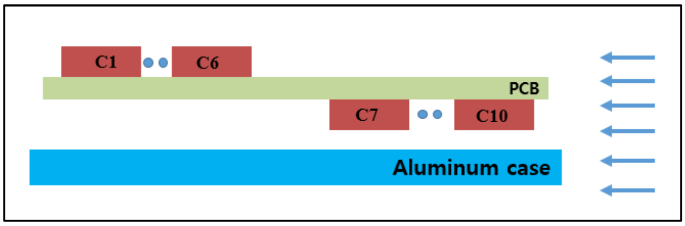


Figure 3.7 – The illustration of control module type II with major components

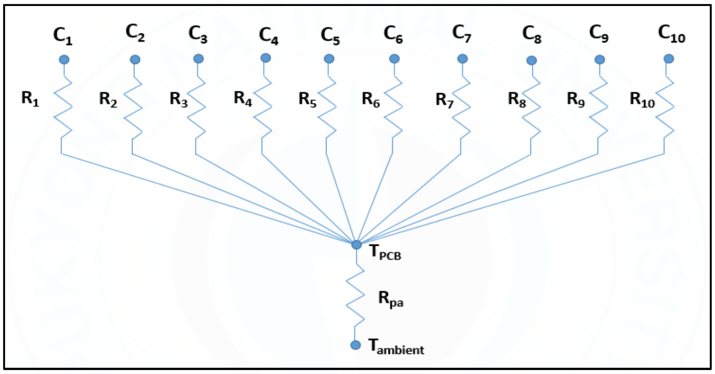


Figure 3.8 – Thermal network for initial design of control module type II

A number of selected key components was described in Figure 3.7 with several components mounted on the upper side of PCB and others located on lower side that closed to the aluminum case. It is clearly seen that there is no thermal contact between the case and major heat sources. In other words, the aluminum case does not have any role in thermal consideration of this control module. The heat dissipated by those components only carried out by air cooling convection. Therefore, a network for the original design of control module type II can be explained as shown in Fig. 3.8.

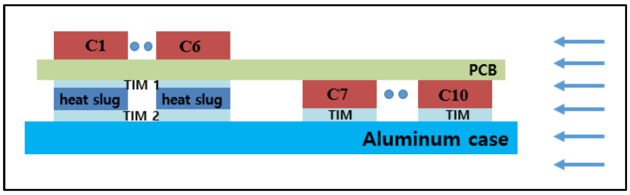


Figure 3.9 – The illustration of improved design for control module type II

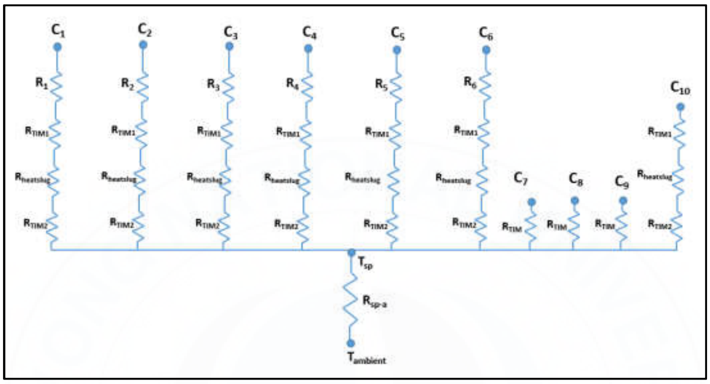


Figure 3.10 – Thermal network for improved design of control module type II

By applying the thermal packaging solution, the thermal paths are created to transfer heat generated by electronic components during system operation. In this case, the aluminum case is not only considered as mechanical structural design but also worked as a good heat spreader thanks to its high thermal conductivity and better heat transfer convection coefficient compared to the poor convective heat transfer of PCB in case of initial design. A thermal resistance network model was developed based on 1-D conduction and convection as shown in Fig. 3.10.

3.3.4 Thermal Network Model for Thermal Vias Application

In recent electronic systems, a wide variety of surface mounted devices (SMD) including active and passive components calls for the extremely high quality of printed circuit boards (PCBs). Besides the allowed advantages of SMD, there is a great challenge of the aforementioned components related to the extracting heat from them [6]. Therefore, it cannot be denied that PCBs have the crucial roles on the effectiveness of thermal consideration of SMD components. The high dependence of thermal resistance between junction to ambient is proven and the idea of applying thermal vias to solve the problem of thermal designs for PCBs has already widely used [7]. Through thermal vias, the waste heat generated during operation is effectively conducted to the extended thermal management such as heat sink or heat spreader. Hence, thermal performance optimization of an electronic system is not completed without a properly design of thermal vias for PCBs, especially for the valuable control module of semiconductor manufacturing equipment.

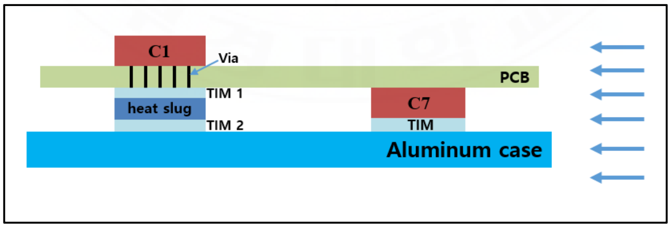


Figure 3.11 – The illustration of improved design for control module type II with thermal vias

As can be seen in Figure 3.11, a number of vias will be added to the PCB in order to improve the heat transfer efficiency from heat sources that located on the upper site of PCB to the thermal packaging and finally being distributed to the ambience by an extended heat spreader.

The Flame Retardant (FR4) is well known for the most popular chosen material of PCBs because of its low cost. However, FR4 has significantly low thermal conductivity which leads to the increase of overall thermal resistance of network. In order to improve the thermal performances of key components mounted on the upper side of PCB, the thermal resistance of PCB should be decreased. There are few possible strategies which can help improving the heat transfer of PCB as increasing the number of copper layers, using better PCB materials, or adding thermal vias. In this research, a certain number of thermal vias located under the crucial electronic components has been created.

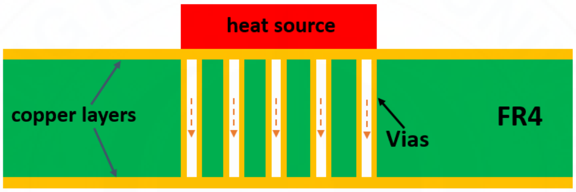


Figure 3.12 Structure of PCB with thermal vias

A schematic diagram of a 2 layer PCB with thermal via is described in Figure. 3 The via design configuration is characterized by following parameters: the via diameter “d” or the drilled hole parameter; the pitch “p” that measured by the distance between center of the adjacent holes, and the plating thickness “t” of via. Besides, vias can be filled with solid materials depending on the process requirements.

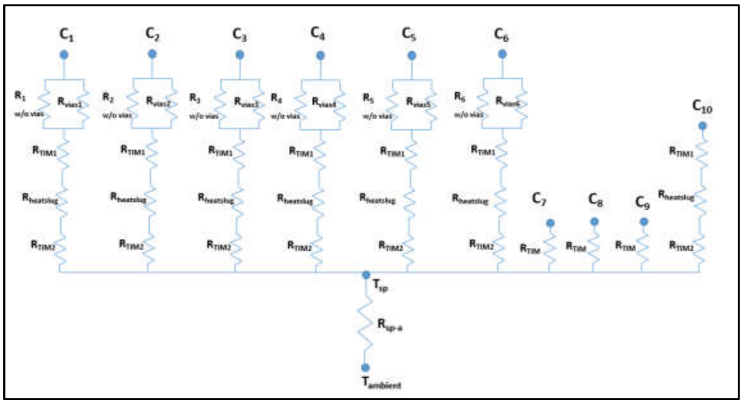


Figure 3.13 Thermal network for design with themal vias

Based on one-dimensional heat transfer assumption, the heat flow paths were presented. It can be clearly seen from Figure 3.10 that without thermal vias, heat from the high heat density components placed on the upper site of PCB will be transferred to the heat spreader by conducting through PCB and thermal packaging, then, being distributed to the ambience by convection. On the other case, with thermal vias added to the PCB, the heat flow paths can be described as following: a significant part of heat generation is transferred from upper side to lower side of PCB by conduction through thermal via and the remaining conducted through PCB, and conducting through thermal packaging before delivered to surrounding by air cooling convection.

For all aforementioned thermal network models, the thermal resistances are calculated by the following formulas. For heat conduction, the thermal resistances can be obtained by:

$$R = \frac{\Delta z}{k.A} \qquad (1)$$

where Δz [m] is the distance between two temperature nodes, A $[m^2]$ is the cross sectional area where the heat flows, and k $[W/m.K]$ is a thermal conductivity.

For the heat convection, the thermal resistance is expressed by:

$$R = \frac{1}{hA} \qquad (2)$$

where h $[W/m^2.K]$ is the heat transfer coefficient, and A $[m^2]$ is the surface area [8].

The corresponding thermal resistances of TIMs, Cu heat slugs, aluminum case and airflow convection are determined by applying the aforementioned expressions.

For estimating the downward parallel plate fin heat sink thermal resistance

$$R_{hs} = \frac{1}{h.(A_{base} + N_{fin}\eta_{fin}A_{fin})} \qquad (3)$$

η_{fin} is the fin efficiency

A_{fin} is the surface area for each fin

A_{base} the exposed base surface area between fins

For further calculation, the following nomenclatures are defined: W, H, L and t_{fin} are the width, the height, the length and the thickness of the heat sink, respectively.

The gap between the fins are determined by: $b = \frac{W - N_{fin}.t_{fin}}{N_{fin} - 1}$

The exposed base surface area can be obtained from: $A_{base} = (N_{fin} - 1)bL$ and the area of one fin is: $A_{fin} = 2H_f L$.

For determining the heat transfer coefficient, the following equation is employed, relating to the Nusselt number, Nu, the Reynolds number, Ra, and Pr number [9].

$$\overline{Nu_L^s} = \left[1 + 0.24\exp\left(-0.0025L^*\right)\right]0.46Ra_L^{0.2} \qquad (4)$$

where $L^* = \frac{L}{\sqrt[3]{\alpha\nu / g}}$

$$\overline{Nu_L} = \frac{\overline{Nu_L^s}}{1 + \frac{H}{a}}\left[\exp\left(-\frac{H}{2a}\right) + 0.65\left(\frac{H}{a}\right)\left(\frac{L}{a}\right)^{-\frac{4}{5}} Ra_L^{\frac{1}{5}}\right]$$

where $Ra_L = \frac{g\beta\left(T_s - T_\infty\right)L^3}{\nu^2}\Pr$

The Prandtl number is $\Pr = \frac{\mu.c_p}{k}$

The heat transfer coefficient is $\overline{h} = \overline{Nu_L}.\frac{k_{air}}{L}$

The fin efficiency can be calculated by: $\eta_{fin} = \frac{\tanh(m.H_f)}{mH_f}$ where $m = \sqrt{\frac{2h}{k_{fin}.t_{fin}}}$

Finally, the total thermal resistance of the heat sink is:

$$R_{total} = R_{hs} + \frac{H - H_f}{k_{base} W.L} \qquad (5)$$

For the initial design of control module type I, the excessive temperatures between the heat sources and the ambient is evaluated by:

$$\Delta T_i = T_{Ji} - T_\infty = \Delta T_{sp} + q_i.R_i \quad (i = 1 \div 8) \qquad (6)$$

and

$$\Delta T_9 = T_{J9} - T_\infty = (R_{pcb-total} + R_{pcb-9}).q_9 \qquad (7)$$

Similarly, for control module type II, the excess temperatures between components and ambient were determined by following expressions:

$$\Delta T_j = T_{Jj} - T_\infty = \Delta T_{PCB} + q_j.R_{pcb-j} \ (\mathrm{j} = 1 \div 10) \qquad (8)$$

When the thermal improvement solutions were added to each control module, the temperature differences between components and the ambient were calculated by:

$$\Delta T_i = T_{Ji} - T_\infty = \Delta T_{hs} + q_i.R_i \quad (i = 1 \div 9) \qquad (9)$$

and $\Delta T_j = T_{Jj} - T_\infty = \Delta T_{enlosure} + q_j.R_j \quad (\mathrm{j} = 1 \div 10) \qquad (10)$

for control module type I and type II, respectively.

In case of applying thermal vias, the excess temperatures are evaluated by similar method as for control module type II. However, instead of using R_{PCB}, the resistances of thermal via pads will be used. The calculation process for thermal via pads resistance [10] as following:

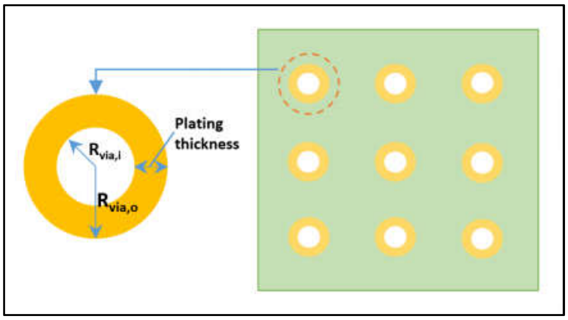


Figure 3.14 Detailed structure of thermal via

The thermal resistance of single via in the direction through the PCB is

$$R_{via} = \frac{l}{k_c \pi (r_{via,o}^2 - r_{via,i}^2) + k_f \pi r_{via,i}^2} \qquad (11)$$

where l is the length of the via, k_c is thermal conductivity of copper; k_f is the thermal conductivity of the filled material that fills the via, for instance, through hole via is considered as air filled via, and other materials such as copper, aluminum; $r_{via,o}$, $r_{via,i}$ are outer and inner radius of the via, respectively. The heat flow path through via copper plating is considered as parallel with the heat path that created by remain via pad area without via. Supposing that the thermal via pad has thickness t; a number of vias N; and k is the normal thermal conductivity of FR4 material, the normal resistance of the portion of thermal via pad without thermal via is:

$$R_n = \frac{t}{k_n (A - \pi N r_{via,o}^2)} \qquad (12)$$

where A is the area of thermal via pad.

The thermal resistance of thermal via pad is obtained by the equivalent parallel resistance of N vias and normal thermal resistance of the area of pad with no thermal vias:

$$\frac{1}{R_{n,via}} = \frac{N}{R_{via}} + \frac{k_n(A - \pi N r_{via,o}^2)}{t} \tag{13}$$

Chapter 4

NUMERICAL MODELS

In this section, the computational investigation of the design solution to improve the thermal performances of several actual complicated electronic control modules for sophisticated semiconductor manufacturing equipment. At first, the investigation of the 3-D computational simulation of initial designs and the improvement by applying our proposed thermal packaging solutions based model structures employing a commercial CFD software package, ANSYS Icepak [18] to show the efficiency of new designs on thermal performances. Secondly, the effects of thermal vias on thermal packaging solution for thermal management of a representative control module were conducted.

4.1 Governing equations

The fundamental governing equations for fluid dynamics, the continuity, momentum, and energy equations. These equations is the physics behind fluid dynamics which describe a given problem and the finite different equations. The computations for the control module type I and type II under both natural and forced convection on a three dimensional laminar flow of air. The governing equations for a steady state flow, a steady state heat transfer, and an incompressible fluid are shown in equations 14-22 [19]

Continuity equation:

$$\frac{\partial u}{\partial x}+\frac{\partial \upsilon}{\partial y}+\frac{\partial w}{\partial z}=0 \qquad (14)$$

Momentum equations:

$$u\frac{\partial u}{\partial x}+\upsilon\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho}\frac{\partial P}{\partial x}+v\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right) \quad (15)$$

$$u\frac{\partial \upsilon}{\partial x}+\upsilon\frac{\partial \upsilon}{\partial y}+w\frac{\partial \upsilon}{\partial z}=-\frac{1}{\rho}\frac{\partial P}{\partial y}+v\left(\frac{\partial^2 \upsilon}{\partial x^2}+\frac{\partial^2 \upsilon}{\partial y^2}+\frac{\partial^2 \upsilon}{\partial z^2}\right)+g\beta\left(T-T_\infty\right) \quad (16)$$

$$u\frac{\partial w}{\partial x}+\upsilon\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=-\frac{1}{\rho}\frac{\partial P}{\partial z}+v\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right) \quad (17)$$

Energy equations:

$$u\frac{\partial T}{\partial x}+\upsilon\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial w}=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right) \quad (18)$$

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}=0 \quad (19)$$

In case of forced convection, the momentum equations are expressed as:

$$u\frac{\partial u}{\partial x}+\upsilon\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho}\frac{\partial P}{\partial x}+v\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right) \quad (20)$$

$$u\frac{\partial \upsilon}{\partial x}+\upsilon\frac{\partial \upsilon}{\partial y}+w\frac{\partial \upsilon}{\partial z}=-\frac{1}{\rho}\frac{\partial P}{\partial y}+v\left(\frac{\partial^2 \upsilon}{\partial x^2}+\frac{\partial^2 \upsilon}{\partial y^2}+\frac{\partial^2 \upsilon}{\partial z^2}\right) \quad (21)$$

$$u\frac{\partial w}{\partial x}+\upsilon\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=-\frac{1}{\rho}\frac{\partial P}{\partial z}+v\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right) \quad (22)$$

where $x, \mathrm{y}, \mathrm{z}$ are cartesian coordinate direction, y is the direction parallel to the gravitational acceleration, x and z are the direction normal to the gravitational acceleration. u, υ, w are flow velocity in

x, y, z direction, respectively. ρ is density, P is pressure, v is kinematic viscosity, g is gravity, β is volumetric thermal constant, T is temperature, T_∞ is the temperature of a free stream, and α is thermal diffusivity.

4.2 Computational models and boundary condition

This section describes the computational models and boundary conditions of control modules numerical thermally analysis. A variety of parametric conditions are simulated in order to access the thermal behaviors of the control modules of semiconductor manufacturing equipment which are summarized in Table I. For control module type I, the aluminum heat spreader is replaced by a downward plate fin heat sink with the reasonable fin height of 5 mm. The space between two fins, and the thickness of fin are simulated. For control module type I, the heat transfer paths are created to make use of the aluminum case for the heat management purpose as a good heat spreader. Different air velocities are considered in case of forced convection. Besides, the effects of thermal interface materials [15] on the effectiveness of thermal packaging solution are investigated. In addition, the study of thermal vias effects on thermal packaging performances is also conducted.

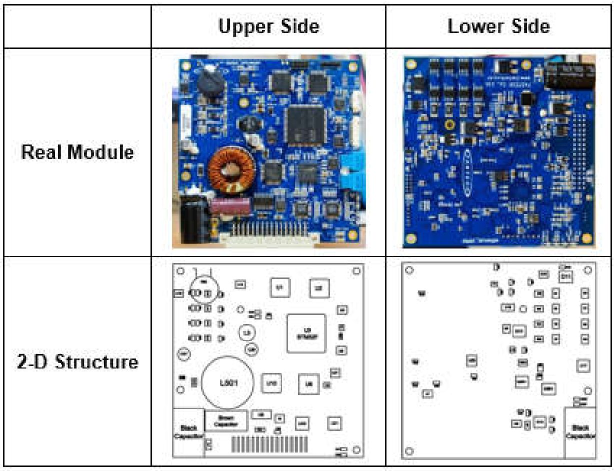


Figure 4.1 Physical structure of TYPE I control module

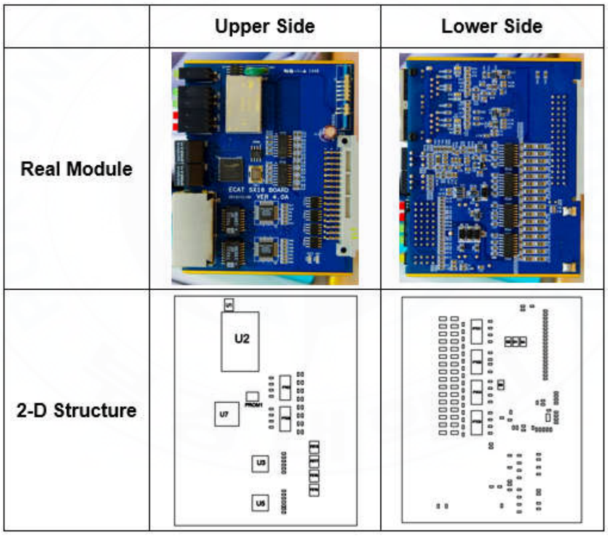


Figure 4.2 Physical structure of TYPE II control module

To predict the temperature fields of five actual control modules, the computational thermal-fluid analysis for each one was conducted by employing a commercial CFD package, ANSYS Icepak considering three different conditions: the initial design and the improved design with thermal solutions including two separated material properties. Fig. 7 and Fig. 8 show two representative designs of five control modules for the semiconductor manufacturing equipment. It can be clearly seen that electronic components are mounted on a complicated printed circuit board (PCB).

Table I: Physical Designs of Control Modules

Modules	Board area	Heat dissipations
TYPE I	100 x 97.8 mm^2	8.006 W
TYPE II	97.08 x 76.65 mm^2	2.265 W

Table II: TIMs thermal conductivities [11-14]

TIMs	Materials	Thermal Conductivity (W/m-K)
TIM 1	Thermal Pad	1
TIM 2	Graphene/Epoxy Composite	3.6
TIM 3	Graphene-Polyolefin Composite	5.6
TIM 4	Graphene-Polymer Composite	12.1
TIM 5	Graphene, Boron Nitride fillers	21.6

Table III: Summary of parameter condition for simulation

Parametric	**Number of fins**	**Fin thickness**	**TIM thermal conductivity**
Fin spacing effect	15 20 25 30	1.0 mm	1 W/mK
Fin thickness	20	1.0 1.5 2.0	1
TIM thermal conductivity	20	1.0	1.0 3.6 5.6 12.1 21.6

Table IV: Summary of parameter condition for simulation of control module type II

Parametric	Air Velocity	TIM conductivity
Velocity Effect	0 1.0 2.0 3.0	1
TIM Conductivity Effect	0	1 3.6 5.6 12.1 21.6

Table V: Summary of parameter condition for thermal vias effect

Parametric	Number vias	Via diameter	Plating thickness	Filled materials
Total number vias effect	32 48 64	1.0	0.04	Air
Via diameter effect	64	0.7 1.0 1.5	0.04	Air
Plating thickness effect	64	1.0	0.02 0.04 0.08	Air
Filled materials effect	64	1.0	0.04	Cu, Al, Si

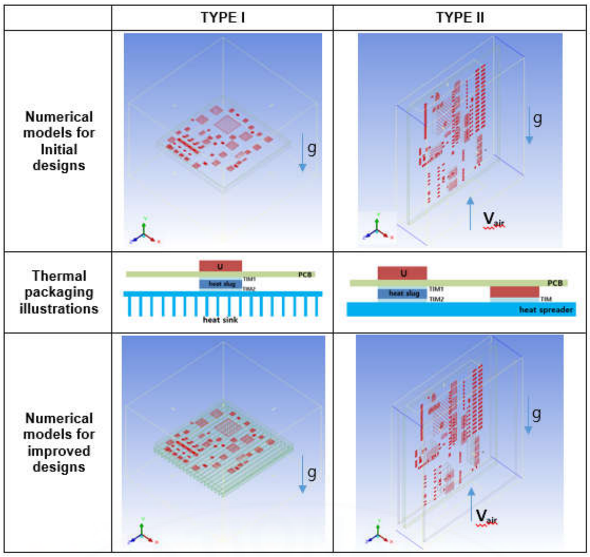


Figure 4.3 Numerical modeling of initial designs; improved designs; and illustration of thermal packaging.

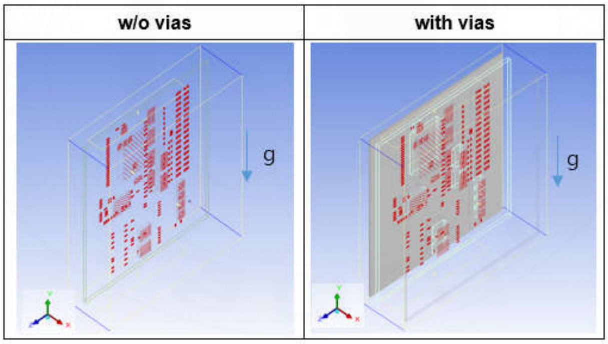


Figure 4.4 Numerical modeling of improved designs without PCB vias and with PCB thermal vias.

Figure 4.3 and Figure 4.4 illustrate the numerical modeling for the initial designs, thermal improved designs, and the module with PCB thermal vias included. In the computational models, all active components are presented as solid blocks with heat sources plated on the tops. Other passive components such as resistors and capacitors are modeled as plantar heat sources. Besides, the thermal vias are represented by the thermal via pads with a certain number of vias and placed under the blocks of active heat sources that located on upper side of PCB.

Chapter 5

RESULTS AND DISCUSSIONS

5.1 Temperature and flow fields

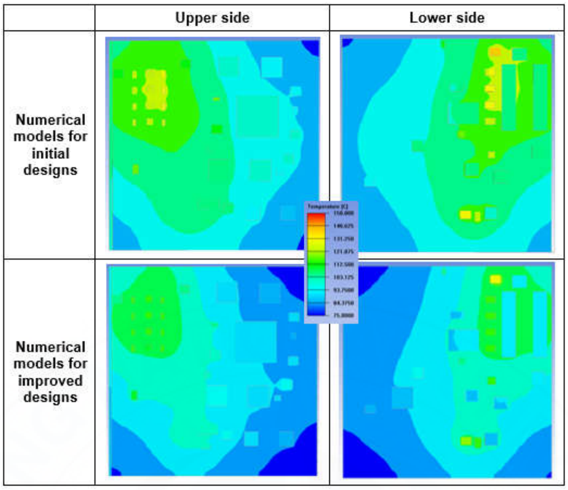


Figure 5.1 Temperature fields of initial design and improved design for TYPE I control module.

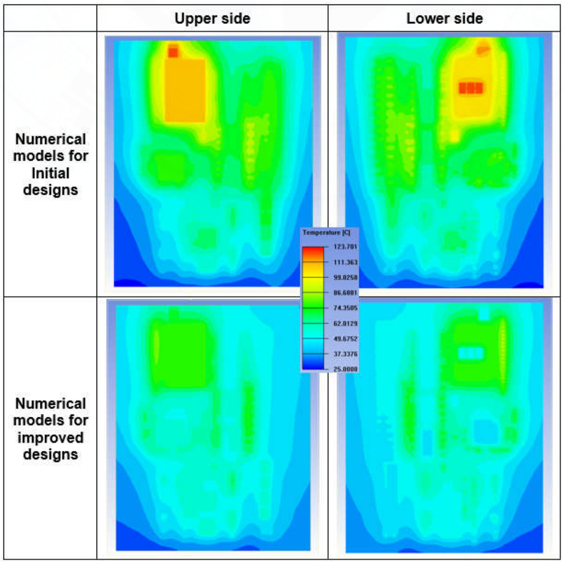


Figure 5.2 Temperature fields of initial design and improved design for TYPE II control module under natural convection.

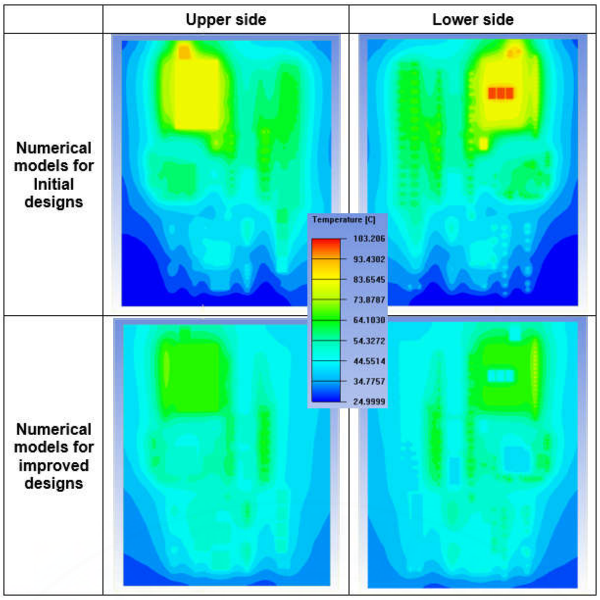


Figure 5.3 Temperature fields of initial design and improved design for TYPE II control module under forced convection.

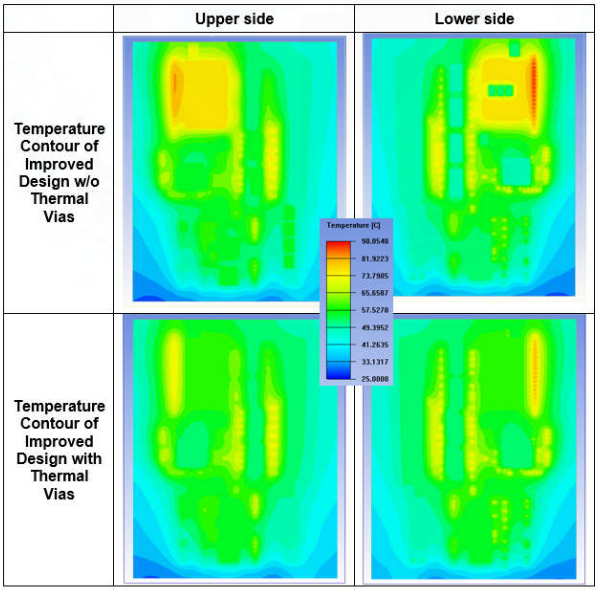


Figure 5.4 Temperature fields of improved design of control module with and without vias under natural convection.

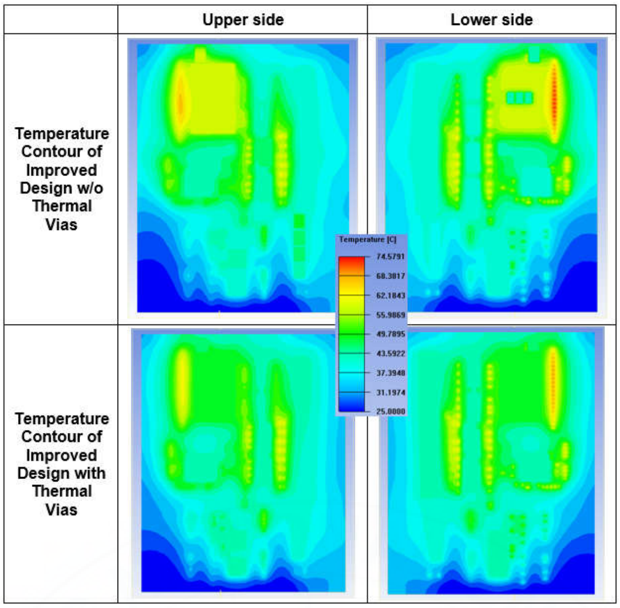


Figure 5.5 Temperature fields of improved design of control module with and without vias under forced convection.

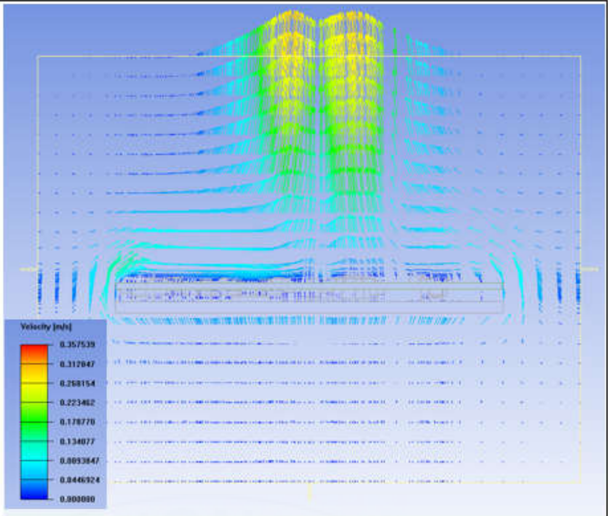
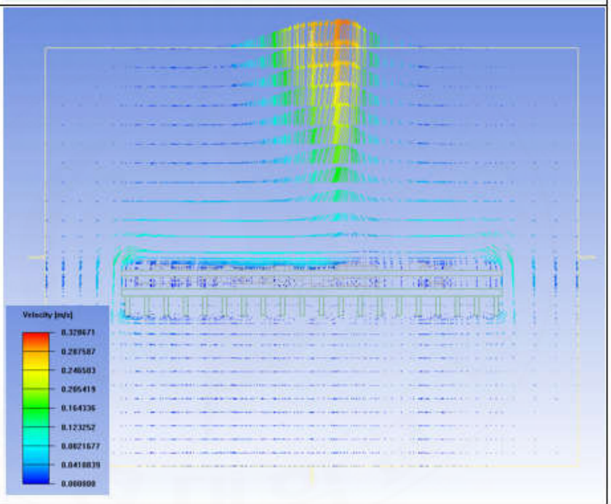
Air Flow Field of Initial Design	
Air Flow Field of Improved Design	

Figure 5.6 Air flow fields of initial and improved designs for TYPE I control module.

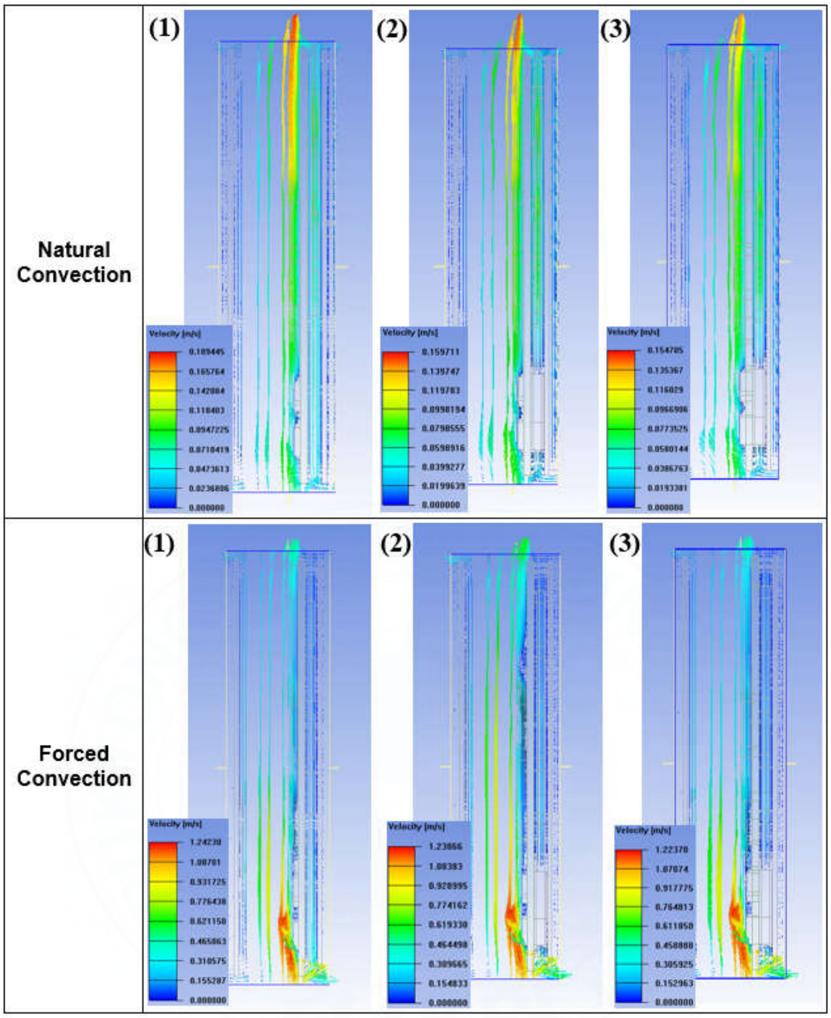


Figure 5.7 Air flow fields of initial (1), improved (2), and improved with vias (3) designs for TYPE II control module under natural and forced convection.

Figure 5.1 shows the temperature fields of both sides of control module type I before and after applying thermal improvement solution. The maximum temperatures of major electronic components are reduced from 13.4% to 17.3% in comparison with initial design. The better performance of applied heat sink and more efficient heat transfer of thermal packaging are significantly contributed to the improvement of thermal behaviors.

Figure 5.2 and Figure 5.3 illustrate the temperature performances of control module type II under natural and forced convection, respectively. It can be clearly seen that a dramatic reduction of temperatures was recorded under both natural and forced convection. In details, the maximum temperatures of high heat density components are lower about 67.3% compared to the initial design. The other considered points, the temperatures also reduced from 20% to 50%. Similarly, under forced convection, a considerable decrease of temperatures is witnessed with 20% to 71% temperature lower. These phenomenon can be explained by the effectiveness of thermal packaging solution that creates great thermal path in order to transfer heat generated during system operation to the heat spreader.

Figure 5.4 and Figure 5.5 indicate the thermal behaviors of control module type II when PCB thermal vias are included under natural and forced convection, respectively. The significant improvements can be seen from the numerical results. The maximum temperatures of crucial electronic components located on upper side of PCB are lowered down from 12.8% to 36.5%. However, an interesting phenomenon of the slight increase of excess temperatures of components on lower site is obtained. The overlapping of location is an appropriate reason to explain the temperature raise of several key components.

Figure 5.6 and Figure 5.7 show the air flow fields of module control type I and type II respectively. The air velocity fields of control module type I show symmetric and fully developed of buoyancy force.

Figure 5.7 illustrates the air velocity of control module type II under different boundary conditions.

5.2 Parametric Studies

5.2.1 Effects of number of fins

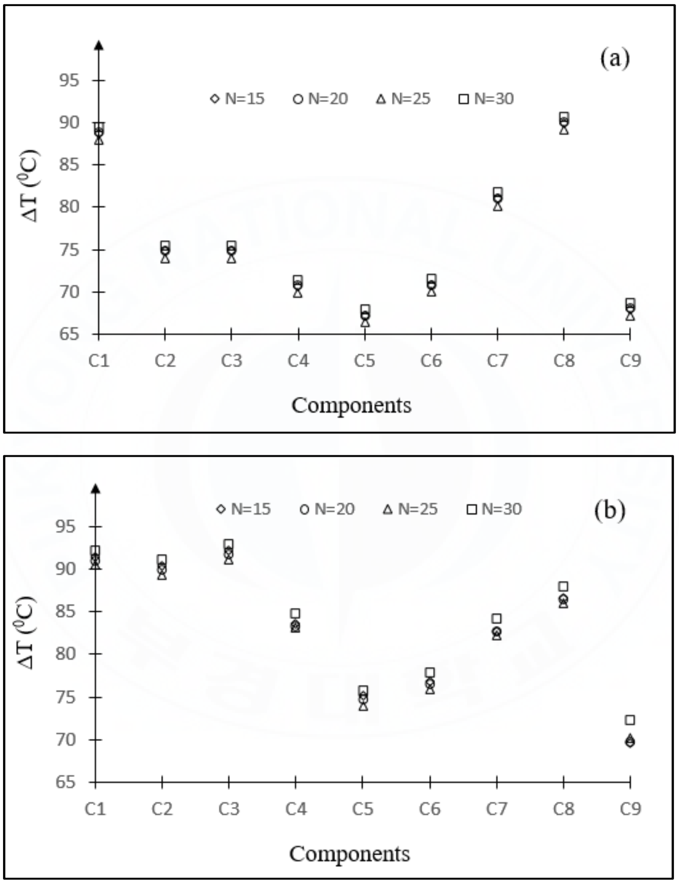


Figure 5.8 Fin Spacing Effects on TYPE I –
Simulation (a) and Thermal Network (b)

This part explains the effects of number of fins on the thermal behaviors of control module type I. A numerical analysis was conducted for number of fins of 15, 20, 25, and 30 plate fins with the

TIM thermal conductivity of 1 W/mK under natural convection. Besides, the thermal network model was also analyzed with the similar parameters as in computational investigation. Figure 5.8 shows the numerically predicted excess temperatures and the results obtained from thermal network analysis of module control type I. The 25-fin heat sink was proved its best thermal performance, and then being the reference throughout the entire study.

5.2.2 Fin thickness effects

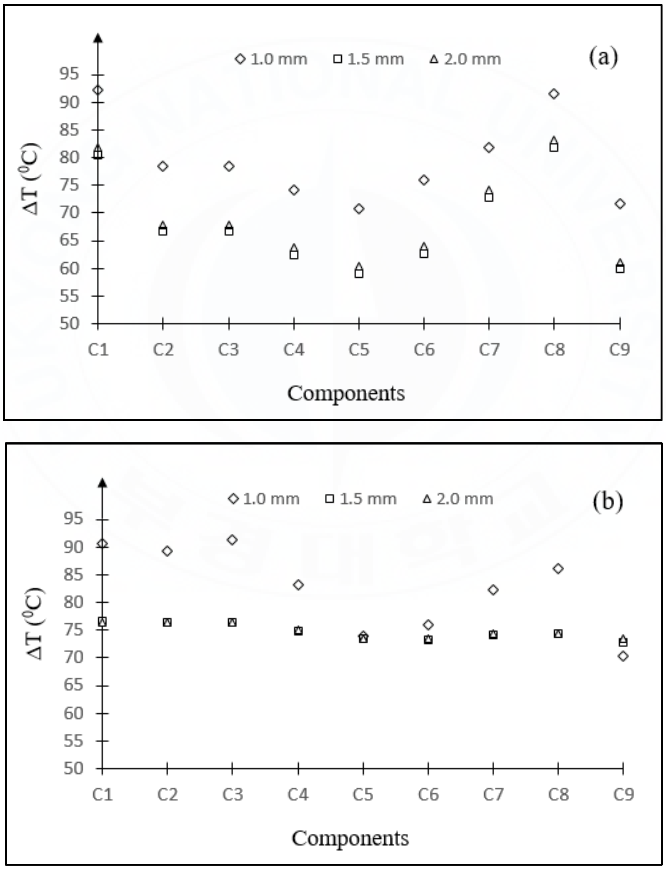


Figure 5.9 Fin thickness effects on TYPE I – Simulation (a) and Thermal Network (b)

Figure 5.9 indicates the effects of fin thickness on thermal performances of control module type I. A numerical study and data extracted from thermal network model show that the fin thickness of 1.5 mm performed the better thermal effectiveness compared with 1.0 mm and 2.0 mm thickness fins in the similar condition of natural convection with 25 fin heat sink.

5.2.3 TIMs thermal conductivities effects

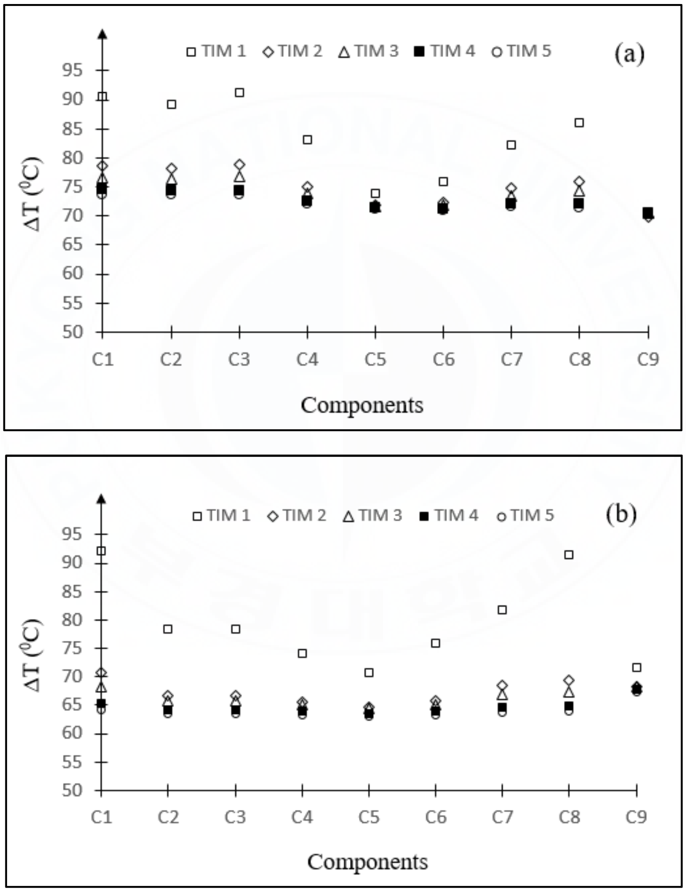


Figure 5.10 TIMs Thermal Conductivities Effects on TYPE I – Simulation (a) and Thermal Network (b)

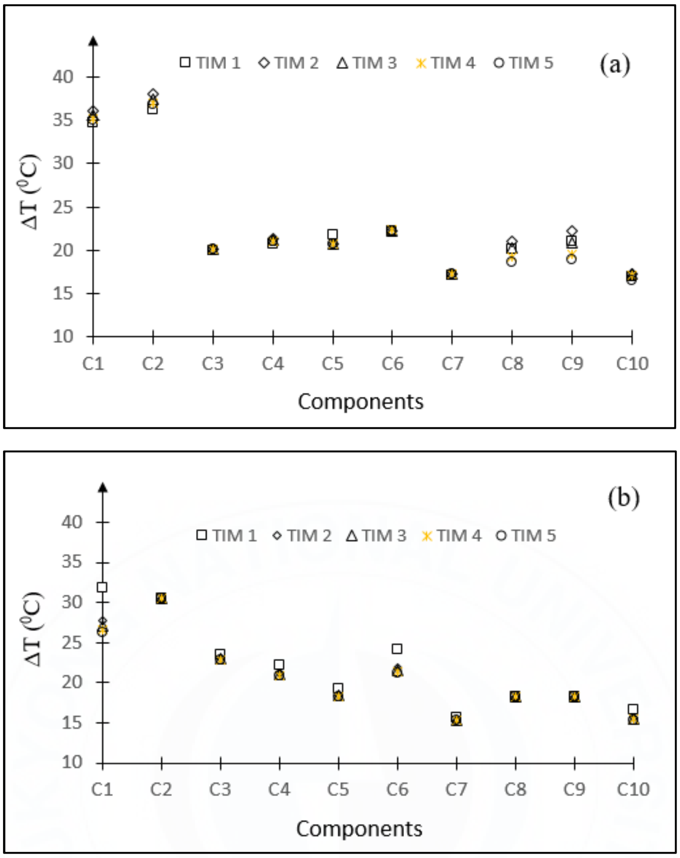
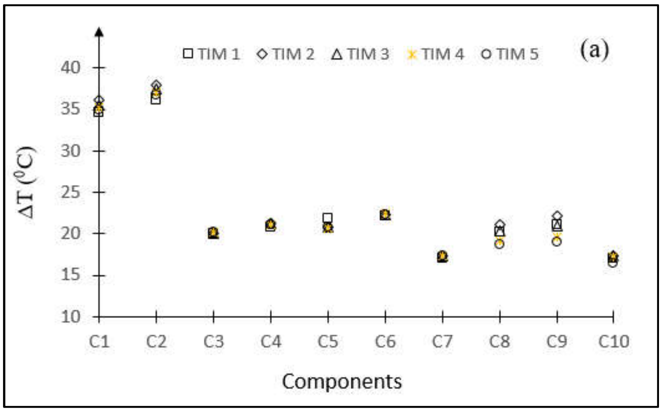


Figure 5.11 TIMs Thermal Conductivities Effects on TYPE II under natural convection – Simulation (a) and Thermal Network (b)



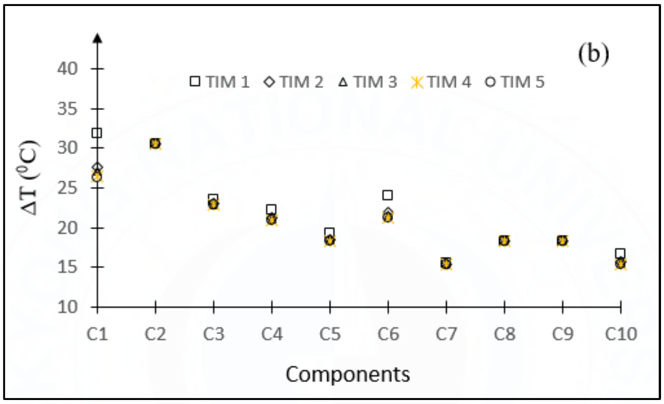


Figure 5.12 TIMs Thermal Conductivities Effects on TYPE II under forced convection – Simulation (a) and Thermal Network (b)

As previous section shown, the effectiveness of thermal interface materials (TIMs) was investigated. In our models, five particular TIMs were integrated with thermal packaging for electronic components. In case of packages mounted on the site closed to the heat sink in type I and closes to the aluminum case in type II (acts as the plate fin heat sink), the components are directly attached to the heat sink by a single layer of TIM exist between the package and the heat sink. In addition, by introducing the Copper heat slugs, there are two layers of TIMs, one connects the chip to the heat slug and the second one is between heat slug and the heat sink are applied to create the heat path for components which mounted on upper side of the PCBs. There are five particular types of TIMs [4-7] with different thermal conductivities were used in our study among many available TIMs in the market. Referring to the temperature fields of the high power components, it is clearly seen that the junction temperature of packages is considerably reduced, from more than 20% up to 50%. TIMs, with low thermal resistance, enable the heat dissipating from heat sources to the aluminum case by filling the gaps between surfaces to improve heat conduction. The excess temperature of key components while applying new TIMs property are extracted by simulation and thermal network analysis. The results shown in Figure 21, 22, and 23 conclude that the thermal performance of high heat density components are relatively decreased and after the thermal conductivity reached 5.6 W/mK, the effects of thermal conductivity of TIMs become inferior.

For control module type I, the significant excess temperature decreases were recoreded when the thermal conductivity of TIM increases 3.6 times from 1.0 W/mK to 3.6 W/mK of graphene composite. It is seen that excess temperatures when using TIM 2 are lower than that of using TIM 1 from 2.8% to 13.5%. However, after the thermal conductivity reached 5.8 W/mK of TIM 3, the slight improvements of thermal performances were shown. It can be explained by the thermal resistances of TIM layers show the minor changes that can be negligible when increasing the thermal conductivity of TIMs. For control module type II, the minor decreases of excess temperatures were shown as Fig. 5.11 and Fig 5.12.

The obatained data from thermal network analysis show the relative agreement with the numerically investigated models.

5.2.4 Air velocity effects

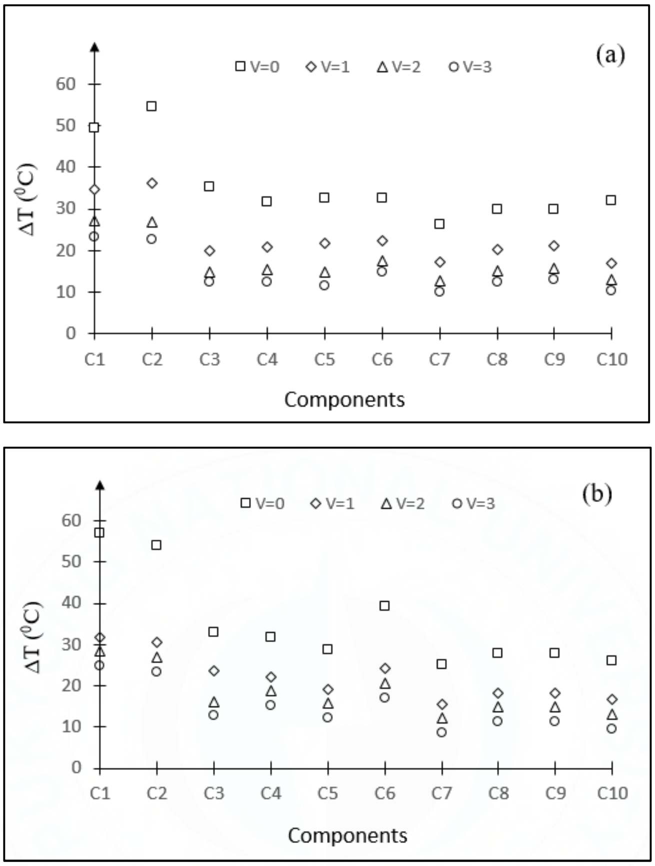


Figure 5.13 Air Velocity Effects on TYPE II – Simulation (a) and Thermal Network (b)

Considering the control module type II, in case of forced convection, the air velocity of 1 m/s, 2 m/s, and 3 m/s were investigated to illustrate the effects of air velocity on thermal improvement of control modules. Figure 5.13 shows the results from numerical analysis and thermal resistance network analysis. Where, V=0 m/s denotes for the natural convection. From the obtained results, it can be concluded that with the insufficient increase of air velocity, the insignificant improvements were recorded with average 5ºC lower for the increase of air velocity.

5.2.5 Effects of number of via

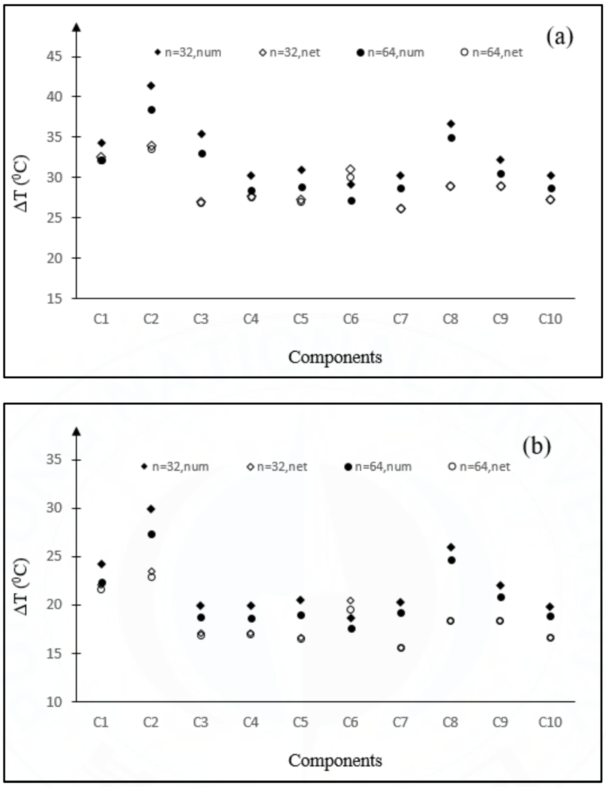


Figure 5.14 Effects of number of vias on excess temperature of key components under natural (a) and forced (b) convection obtained from numerical studies and thermal network analysis

In order to achieve the appropriate number of vias for certain components placed on upper side of PCB, several computational simulations were conducted. With the increase of the number of vias, the excess temperatures of aforementioned components show significant decreases as presented on Figure 14, up to 10% under natural convection and forced convection, respectively.

5.2.6 Via plating thickness effects

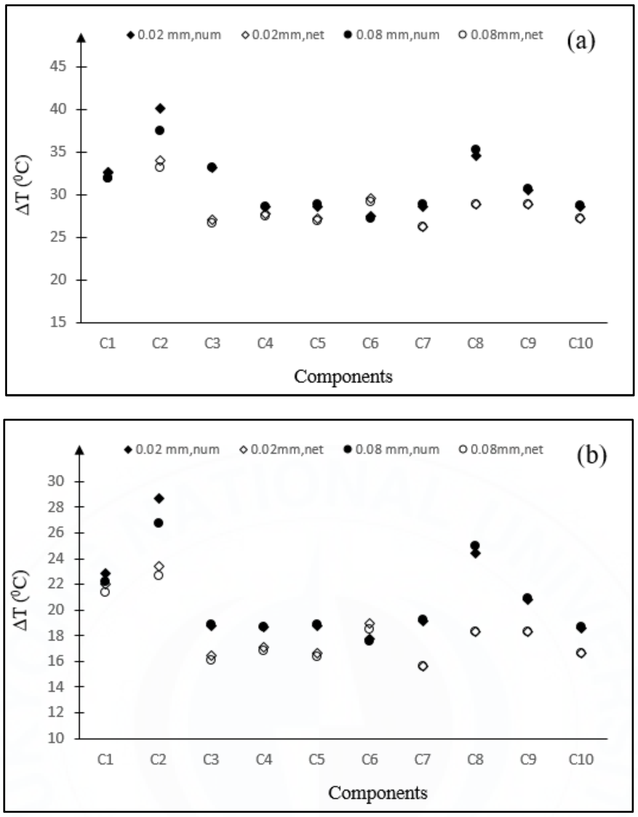


Figure 5.15 Effects of vias plating thickness on excess temperature of key components under natural (a) and forced (b) convection obtained from numerical studies and thermal network analysis

Effects of plating thickness are further analyzed as shown in Figure 5.15 with the given number of vias is 64 and 1.5 mm of diameter, the numerical solution pointed out that the 0.08 mm thickness via has proven itself advantage compared to 0.02 mm thickness via.

5.2.7 Via diameter effects

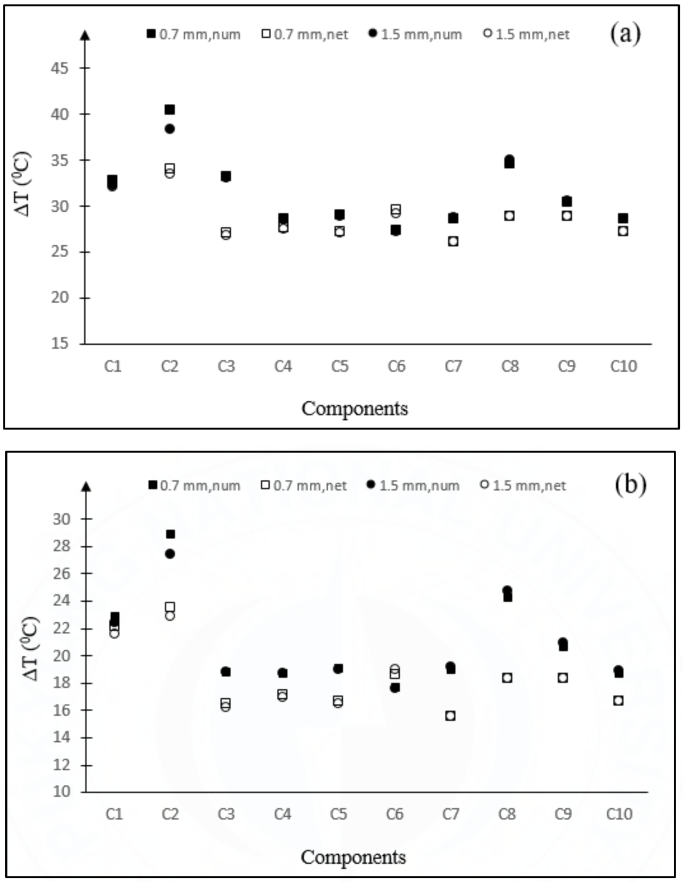


Figure 5.16 Effects of vias diameter on excess temperature of key components under natural (a) and forced (b) convection obtained from numerical studies and thermal network analysis

The effects of via diameter were also analyzed with via diameter of 1.5 mm, the total number of vias is 64. The results obtained from numerical investigation demonstrates that 1.5 mm diameter via provides the best thermal performances amongst vias with 0.7 mm and 1.0 mm diameter on both natural and forced convection conditions. A slight improvement on temperatures of major components was recorded.

5.2.8 Effects of via filled materials

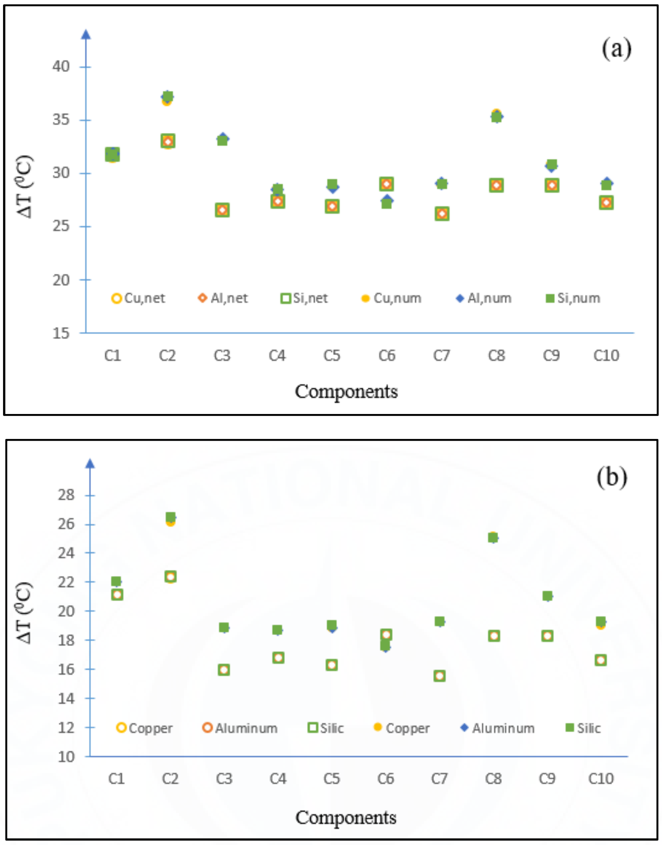


Figure 5.17 Effects of vias filled materials on excess temperature of key components under natural (a) and forced (b) convection obtained from numerical studies and thermal network analysis

Different filled materials for thermal vias are considered by adding copper, aluminum, and silicon to the center hole in each via. The data extracted from numerical analysis indicate that the effect of this term is considerable small and can be neglected without leading to significant effects on the accurate results.

5.3 Comparison between simulations and thermal network models

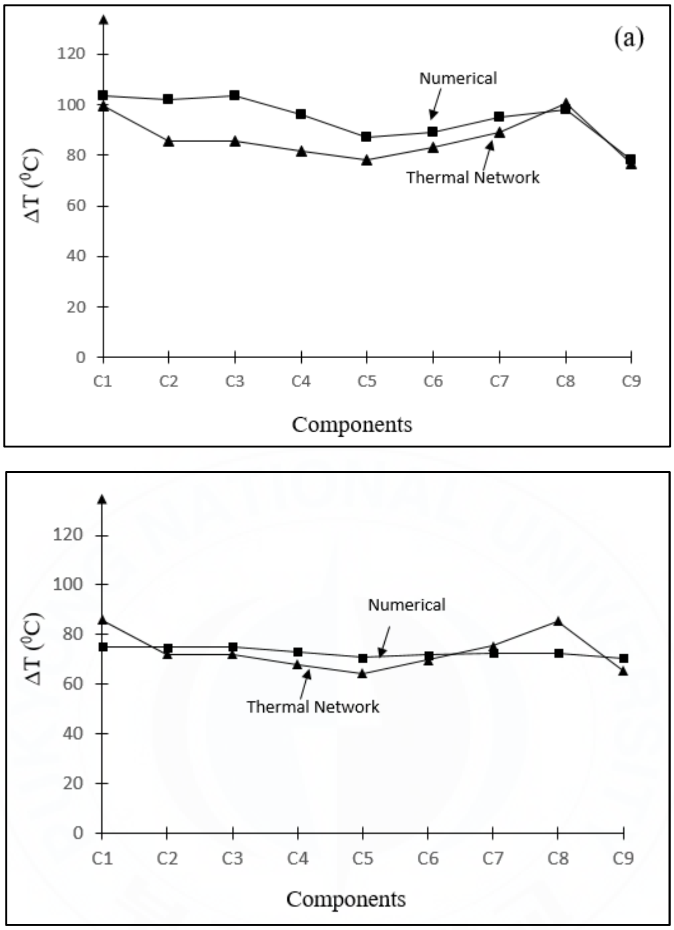


Figure 5.18 TYPE I – Comparison between Numerical and Thermal Network Initial (a) and Improved (b) Designs – Natural Convection

The average discrepancy between numerical results and thermal network analysis found is 8.9% for the initial design of control module type I while for improved design, the average discrepancy was found at 7.8%. The maximum discrepancies are 17.4% and 17.3%, respectively.

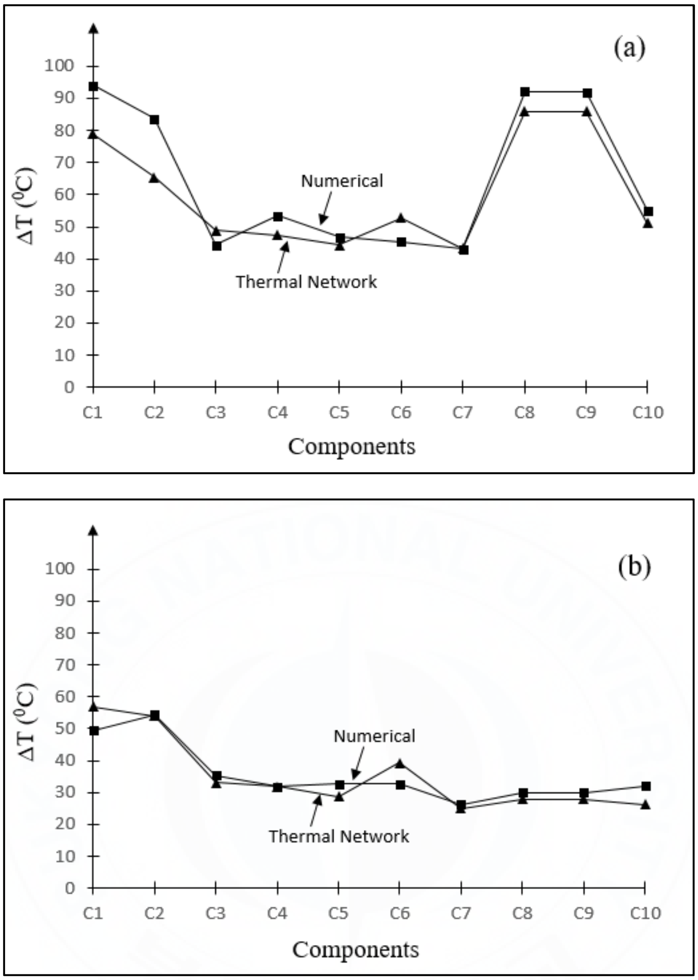
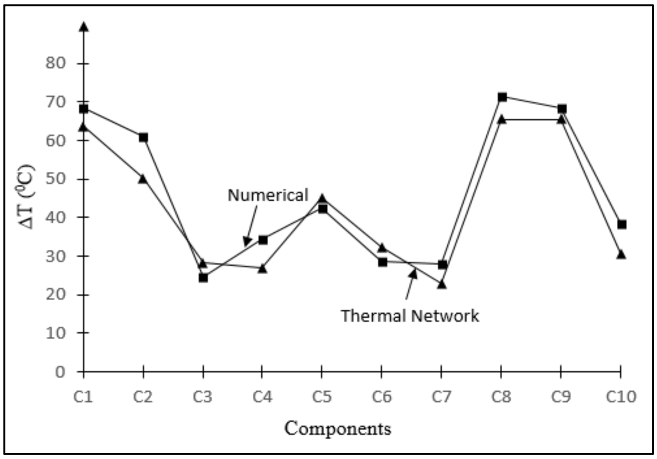


Figure 5.19 TYPE II – Comparison between Numerical and Thermal Network Initial (a) and Improved (b) Designs – Natural Convection

Figure 5.19 shows the excess temperatures extracted form numerical study along with data obtained from thermal network analysis for control module type II. The average discrepancy between computational models and thermal network models of initial design and improved design are 9.6% and 8.6%, respectively.



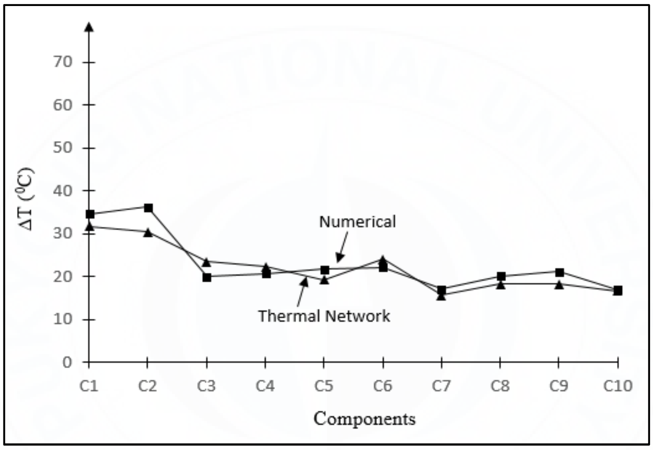


Figure 5.20 TYPE II – Comparison between Numerical and Thermal Network Initial (a) and Improved (b) Designs – Forced Convection

Similarly, results obtained from simulation and thermal network analysis under forced convection are shown in Figure 5.20. The average discrepancy found are 13.8% and 10.4% for initial and improved designs, respectively.

From all above-mentioned results, thermal network analysis shows the relatively agreement to the numerical investigation of thermal behaviors of control modules for semiconductor equipment. Hence, this contribution enables the new approaching of temperature prediction for thermal analysis of electronics in module levels.

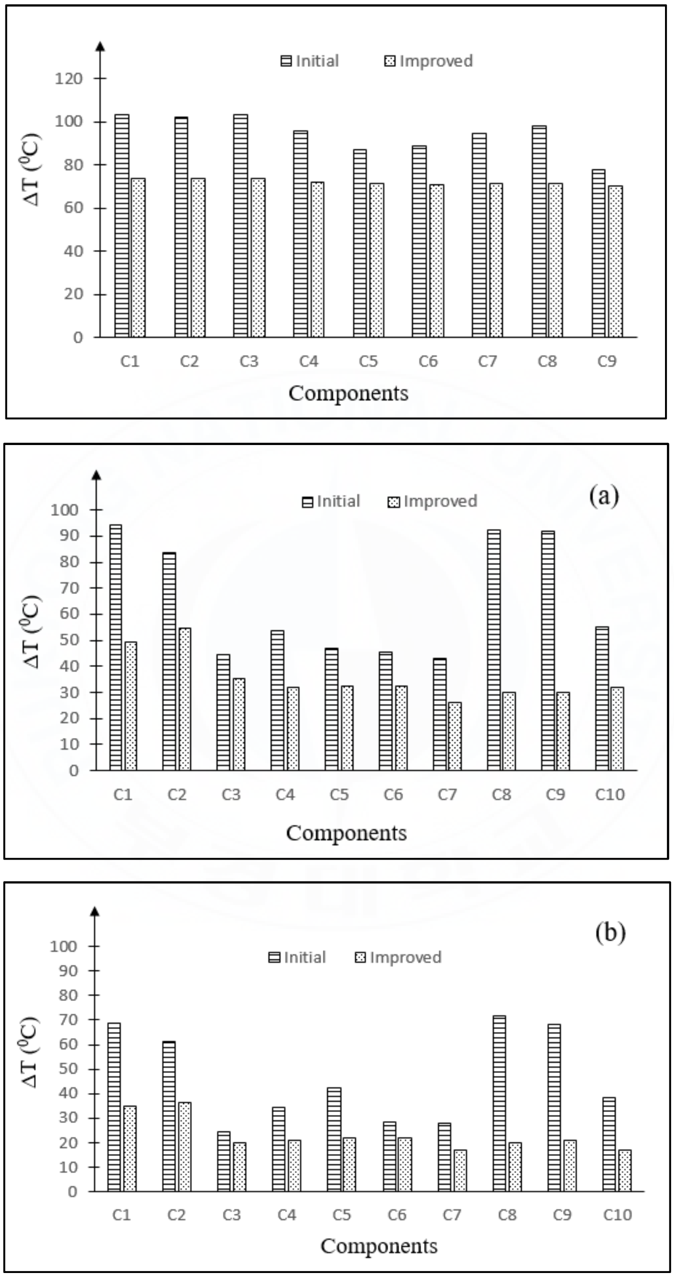


Figure 5.21 Excess Temperatures of key components of Initial and Improved Designs - Control Module Type I and type II under Natural Convection (a) and Forced Convection (b)

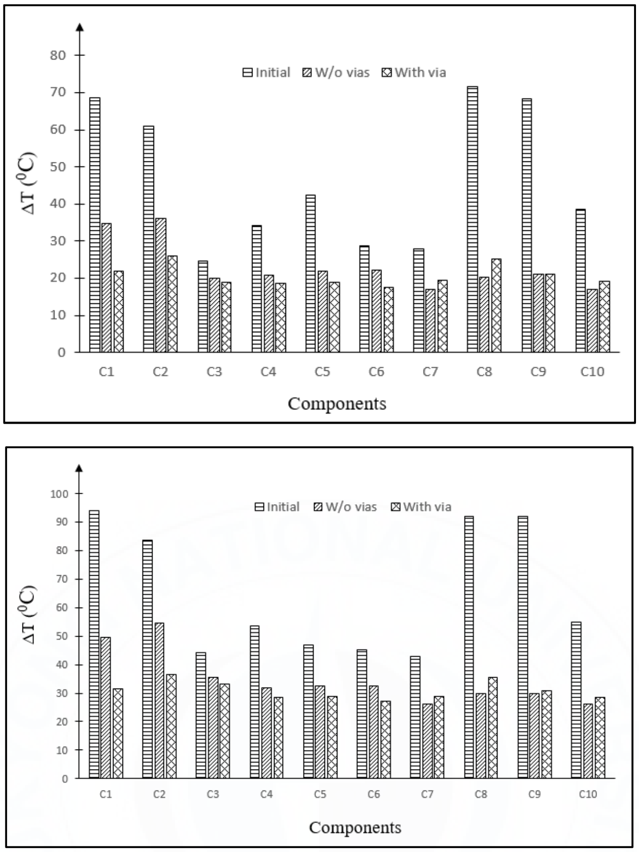


Figure 5.22 Excess Temperatures of key components of Initial and Improved Designs with and without PCB thermal vias

Figure 5.22 and Figure 5.23 indicate the excess temperatures of key components on initial design and improved thermal design modules and compared with the thermal performances while PCB thermal vias were applied when analyzing control module type II. It is clearly seen that the excess temperatures of considered components are significantly reduced by applying the thermal management solution. It may reduce the failure rates or improve the reliability of electronic components on control modules for semiconductor manufacturing equipment.

Chapter 6

CONCLUSION

The thermal packaging solution for thermal performances of control modules for semiconductor manufacturing has been investigated numerically and analytically based on thermal resistance network models. The proposed thermal improvement solutions for two representative control modules with different structures are introduced. The control module type I, with the possibility of space and structural replacement, the extended flat plate fin heat sink was applied. In contrary, the fixed mechanical structure of control module type II refuses the possibility of changing design structure. The aluminum case is used as heat spreader by attaching the key components to the case through extra heat paths. The CFD models were investigated to predict the thermal behaviors of control modules with initial design and after applying thermal improvement solutions. For control module type I, the effectiveness of improved thermal management was modeled under 15, 20, 25, and 30 fins, 1.0 mm, 1.5 mm, and 2.0 mm thickness of fin. In addition, different types of thermal interface materials were used, including: common thermal pad, graphite/epoxy composites, graphite nanoplatelet-epoxy composite, and graphene-polyolefin adhesive composites, composite with graphene and boron nitride fillers with the thermal conductivity ranking from 1.0 to 21.6 W/mK. Similarly, a variety of computational studies was investigate to determine the thermal characteristics of control module type II under natural convection with various TIMs thermal conductivities and the effects of air flow velocity were conducted regarding to forced convection. Furthermore, a comprehensive study on effects of PCB thermal vias on thermal performances of control module was considered.

Some remarkable results were extracted from the numerical modeling for two representative control modules mentioned above. Firstly, the downward heat sink with 25 plate fins, corresponding to the fin spacing of 4.21 mm, and 1.5 mm fin thickness shows the best performance compared with other design parameters. The meaningful improvement can be seen when the thermal conductivity of TIMs increased to 5.8 W/mK (TIM 3), and then the effectiveness of TIMs is insignificant if thermal conductivity continue increasing. Secondly, the investigation on thermal behaviors of the control module type II with different boundary conditions indicates that the thermal conductivity of TIMs show less affection on improvement of reducing junction temperatures of key nodes on module type II with the maximum increase is 10%, approximately. In case of forced convection, the air velocity effects were discovered. The results show that with the inlet air flow velocity increasing its speed, it contributed greatly on reducing temperatures of crucial components. The effects of via design parameters including the thickness of copper plating layer; the diameter of via; the number of vias; and the filled materials are studied. The results demonstrate that the increases of plating thickness, via diameter and the number of vias show the considerably reduced of temperature profiles for considered components. An investigated parametric study on effects of thermal vias shows that with 1.5 mm diameter, 0.08 mm plating thickness vias can decrease the junction temperature of components located on surface of PCB that far from the heat spreader.

Additionally, the analytical models based on thermal resistance network models were studied with certain assumptions. The results obtained from the thermal network analysis show the relatively agreement with the results extracted from computational simulation within the discrepancy of 15%.

These results enable the possibility of applying thermal packaging as the thermal improvement solutions for electronic control modules. Besides, the thermal network models can be introduced as the approaching of simple method to barely predict thermal behaviors for electronics in module levels.

However, in this research, since we assumed the uniform heat flux and the thermal network analysis neglected 3-D effects, thus, some discrepancy between the computational analysis and thermal network model results can be found. In future works, we should improve the accuracy of modeling and research different types of TIMs that has higher thermal conductivity.

LIST OF PUBLICATIONS

1. V.T. Nguyen, K.J. Kim, "Analytical Modelling of Heat Generation in the Phosphor Layer of High Power Light Emitting Diode Packages", The Korean Society of Mechanical Engineers of the Thermal Engineering Division, 2015.
2. V.T. Nguyen, K.J. Kim, "Computationally-Investigated Thermal Behaviors of Control Modules for Semiconductor Manufacturing Machines", The Korean Society of Mechanical Engineers of Reliability Division, 2015.
3. V.T. Nguyen, K.J. Kim, "Investigation of Thermal Network Analysis of Control Modules for Semiconductor Manufacturing Machines", ISAMPE 2015, China.
4. V.T. Nguyen, K.J. Kim, "Compact Thermal Network Model to Investigate Thermal Behaviors of Control Modules of Semiconductor Manufacturing Equipment", The Korean Society of Mechanical Engineers of Reliability Division, 2016.
5. V.T. Nguyen, K.J. Kim, "Numerical Study of Parametric Effects on Thermal Behaviors of Control Modules of Semiconductor Manufacturing Equipment", The Korean Society of Mechanical Engineers of Reliability Division, 2016.

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