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COMPARISON OF DIFFERENT COOLING SYSTEMS USING COMPACT MODEL

Due to the strong influence of temperature rising on integrated circuits performance and reliability, an adequate thermal analysis of their cooling systems is required during chip packaging in order to prevent the thermal catastrophe. In this paper, we propose an approach based on RC compact model, which enables in one hand an approximation of dynamic thermal behaviour and in other hand the accurate temperature computation at any measurement point of parallel plate fin heat sink with U-shape channels. Farther more, we present the impacts of convection coefficient on heat sink surface temperature using a simplified approach, which enables the temperature computation by using the RC thermal compact model. Due to the convection coefficient change of surrounding environment, the surfaces and mass of parallel plate fin heat sink with U-shape channels were reduced while enhancing heat transfer capability.

Keywords: Thermal compact models, integrated circuit, heat sink, temperature, active cooling

1. Introduction

The heat transfer from nowadays' integrated circuits interior to surrounding cooling air remains as a great challenge. Due to the exponential increasing of power density and high power dissipation at high frequency, decreasing the thermal stress has become one of the major issues for integrated circuits designers. Fig.1 describes the experimental results of a research that was performed by Maudgali to determine the causes of microelectronic circuit failures [4]. As depicted in Fig.1, more than the half of the failures are the issues caused by temperature rising.

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Due to the strong influence of operating temperature on the integrated circuits performance and reliability therefore, building an appropriate thermal compact model is needed in the stages of thermal analysis and temperature computation process of package. The thermal compact models may provide a good indicator of the chip thermal capability of a given package.

In order to enhance the thermal management of integrated circuit, one of the common means is the utilization of heat sink [1]. Their use allows the reduction of thermal resistance between circuit and cooling air by extending the exchange surface for heat transfer. They are recognized as effective tools that improve the heat transfer from integrated circuits to the surrounding cooling air. Hence, thermal modelling from integrated circuit to heat sink level is a crucial stage of system's construction. In [11] Andreas Tockhorn, Claas Cornelius, Hagen Saemrow and Dirk Timmermann proposed a method for the fine-grained modelling of temperature distribution in many-core systems based on Networks-on-Chip, which allows designers to model temperature distribution easily. Paper [8] proposed a technique based on co-simulation of packages given with RC compact model and the board, which provides further details of the heat transfer in board and accurate computation of junction temperature in packages. In [9] an algorithm has been presented in order to facilitate the time constant spectrum calculation in thermal simulator programs. The time constant spectrum is defined as the graphical representation of the whole time-constant and R magnitude in the step-function of lumped circuit. It may be used to present dynamic thermal behaviour of packages, assemblies and microsystems. In order to reduce integrated circuits' temperature by using Peltier heat pump and cooling fin, in [2] authors proposed an analytical method, which uses the dissipated power in the circuit as the control parameter to optimize the Peltier current. In [5] the author proposed a new rule for choosing the accurate number of Fourier series terms and for estimation the error in order to compute accurately the temperature over hybrid microelectronic.
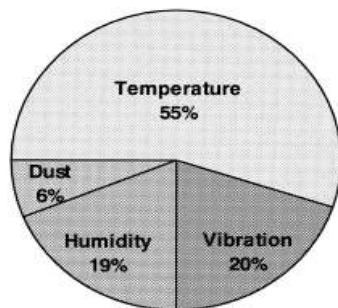

Fig.1 Origins of microcircuit failures [3]

2. Methodology

2.1. Analogy of electrical and thermal parameters

Several techniques have been applied in order to study the dynamic thermal behaviour of microelectronic circuit/system attached to heat sink. Most of those methods are based on RC (resistance and capacitance) thermal compact models. The method of temperature computation described in this paper is based on the analogy between energy flow and the behaviour of RC electrical network [11]. The analogy between electrical and thermal parameters is described in [4].

Charging and discharging the capacitances in RC electrical network one may describe the transient thermal behaviour of a system (package). Fig.2 depicts RC circuit for transient temperature and its response to voltage pulse. Equations (1) and (2) describe the response voltage amplitude A(t) of the circuit (from 0 to U_{in} and from U_{in} to 0, respectively) [6].

$$A(t) = A_0(1 - e^{-t/\tau}) \tag{1}$$

$$A(t) = A_0 e^{-t/\tau} \tag{2}$$

where: t is time in second (s)
 τ is the time constant in second (s)
 A_0 is the output amplitude in volts (v).
It is assumed that the output amplitude reaches its steady state in time 3τ.

$$\tau = R\,C \tag{3}$$

where: R is the resistance in ohms (Ω)
 C is the capacitance in farads (F)

Rising signal		Falling signal	
at t = 0,	A(t) = 0,	at t = 0,	A(t) = A_0,
at t => ∞,	A(t) => A_0,	at t => ∞,	A(t) =>0,
at t = τ,	A(t) = 0.63A_0	at t = τ,	A(t) = 0.37A_0

From above condition, we can estimate thermal time constant for heating of the system as well as for its cooling stage.

The analogies between thermal and electrical parameters enable the modelling of the temperature distribution of the system by using RC electrical circuit. When a component inside integrated circuit is activated, it dissipates a certain amount of heat and becomes a heat source. The investigation described in this

paper is based on a square integrated circuit (heat source) of small lateral dimensions situated at the centre of parallel plate fine heat sink with U-shape channels.
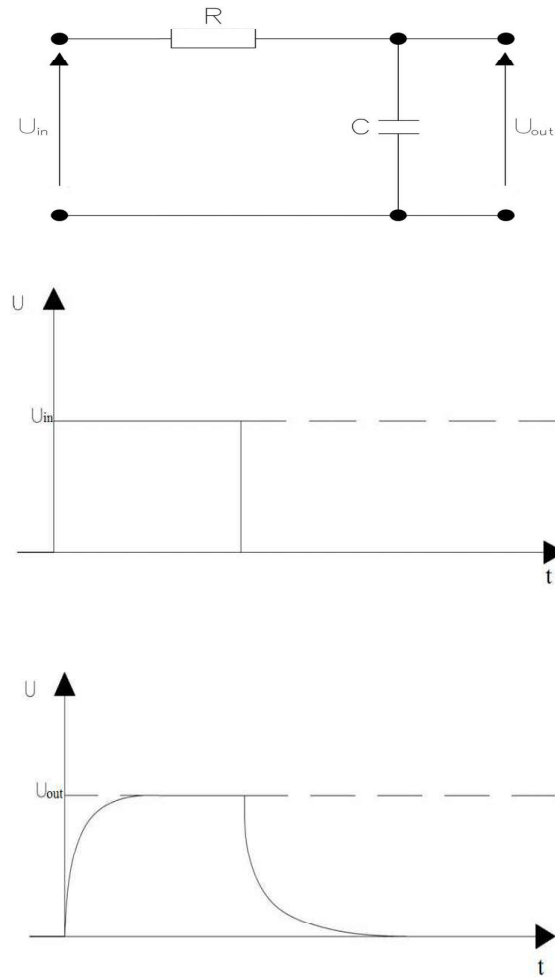

Fig. 2. RC analogue for the temperature transient of integrated circuit and its response to a voltage pulse [6]

The heat sink is made of aluminium, Fig.3 depicts (a) integrated circuits placed on plate fin heat sink geometrical centre, and (b) equivalent thermal network for the structure - RC network model. In order to access one dimension heat transfer we assume that the heat transfer occurs from base surface of integrated circuit to different heat fins of the heat sink.

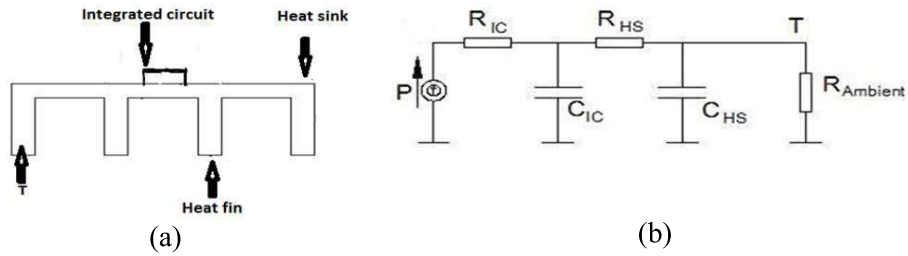(a)   (b)

Fig.3 (a) Integrated circuits placed on plate fin heat sink geometrical centre, (b) Equivalent thermal network for the structure, RC network model, where: P is the power generated by the integrated circuit, R_{IC} and C_{IC} are respectively the thermal resistance and capacitance of integrated circuit, R_{HS} and C_{HS} are respectively the thermal resistance and capacitance of heat sink, $R_{Ambient}$ is the thermal resistance between the heat sink and the ambient, T is heat fin's temperature

2.1.1. Resistance

The Thermal resistance depends on the distance, area of cross section and thermal conductivity of material.

$$R_{th} = \frac{l}{\lambda S} \tag{4}$$

where: R_{th} is the thermal resistance in KW^{-1}
l is the distance between two points in m
S is the area of cross section in m²
λ is the thermal conductivity in $Wm^{-1}K^{-1}$
As the parallel plate fin heat sink with U-shape channels has a certain number of fins therefore, equation (4) may be written as follow:

$$R_{th0} = \frac{\beta}{\lambda \Phi} + \frac{\varepsilon}{\lambda \psi}$$

$$R_{th1} = \frac{\beta}{\lambda(2\Phi + \varepsilon)} + \frac{\varepsilon}{\lambda \psi}$$

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.
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$$R_{thn} = \frac{\beta}{\lambda((n+1)\Phi + (n\varepsilon))} + \frac{\varepsilon}{\lambda \psi} \tag{5}$$

$$n = 0, 1, 2, 3, …$$

where: R_{thn} is the thermal resistance of a specific fin including surface from heat source in KW^{-1}
n is the number of fins whereby n = 0 is the fin nearest to heat source.
β is the heat sink base thickness in m

Φ is the area of space between two fins in m^2
ε is the fin thickness in m
ψ is the fin area in m^2

$$\psi = gb \tag{6}$$

where: g is the heat sink base width in m
        b is the fin height in m

$$\Phi = gz \tag{7}$$

where: z is the fin spacing in m

2.1.2. Capacitance

The thermal capacitance depends on the geometry and physical parameters of material.

$$C_{th} = Mc_p \tag{8}$$

where:
C_{th} is the thermal capacitance in J K^{-1}
M is the mass in kg
c_p is the specific heat in J kg^{-1}K^{-1}
The mass is:

$$M = \rho V <=> M = \rho Se \tag{9}$$

where: ρ is the density in kgm^{-3}
        V is the volume in m^3
        e is the thickness in m

As the parallel plate fin heat sink with U-shape channels has a certain number of fins therefore, equation (8) may be rewritten as follow:

$$C_{th0} = \frac{1}{\rho\beta cp\Phi} + \frac{1}{\rho\varepsilon cp\psi}$$

$$C_{th1} = \frac{1}{\rho\beta cp(2\Phi + \varepsilon)} + \frac{1}{\rho\varepsilon cp\psi}$$

.
.
.

$$C_{thn} = \frac{1}{\rho\beta cp((n+1)\Phi + (n\varepsilon))} + \frac{1}{\rho\varepsilon cp\psi} \tag{10}$$

$$n = 0, 1, 2, 3, \ldots$$

where: C_{thn} is the thermal capacitance of a specific fin including surface from heat source in JK^{-1}

Hence, the resistance between the heat sink and ambient may be calculated by using the formula below [3].

$$R_{amb} = \frac{1}{h\,S} \qquad (11)$$

where: R_{amb} is the ambient resistance in WK^{-1}
         h is the convection coefficient in $Wm^{-2}K^{-1}$

2.2. Temperature computation idea

The basic concept of this work is to divide the heat sink surface area into distributed parameters (Fig.3b) i.e. RC-elements. Therefore, the dynamic thermal behaviour of the heat sink surface may be approximated by charging and discharging the capacitances in RC circuit network in a given time constant. Hence, the two principal stages of temperature calculation are the following:
- First, the thermal parameters i.e. resistances, capacitances and ambient resistance values are calculated by using equation (5), (10) and (11) respectively. The number of heat fins should depend on the desire accuracy and should be equidistant from one to the other. It is assumed that the heat source is situated at the geometrical centre of heat sink base surface and the heat fin surface is isothermal. In order to calculate the ambient resistance, the one-side natural convection is assumed.
- Second, the temperature computation is performed by a circuit simulator (LTspiceIV), the resistances and capacitances value obtained in the first step are used in LTspiceIV RC circuit network. The current source (Power) is used as supply. The circuit is composed of certain amount of resistances and capacitances connected together. The capacitances are directly connected to ground and finally, the whole circuit is connected to the ambient resistance. As result, the voltage values of all nodes in LTspiceIV RC circuit are generated. They are interpreted as the temperature value of different heat fins.

3. Temperature computation algorithm

The calculation of thermal parameters method was based on equations (5), (10) and (11). Their values were used in RC circuit and the temperature compu-

tation was performed by the LTspiceIV, which is a well-known program for electrical circuit simulation. Due to the analogies existing between electrical and thermal parameters, the program allows the thermal analysis of the system, Fig. 4.
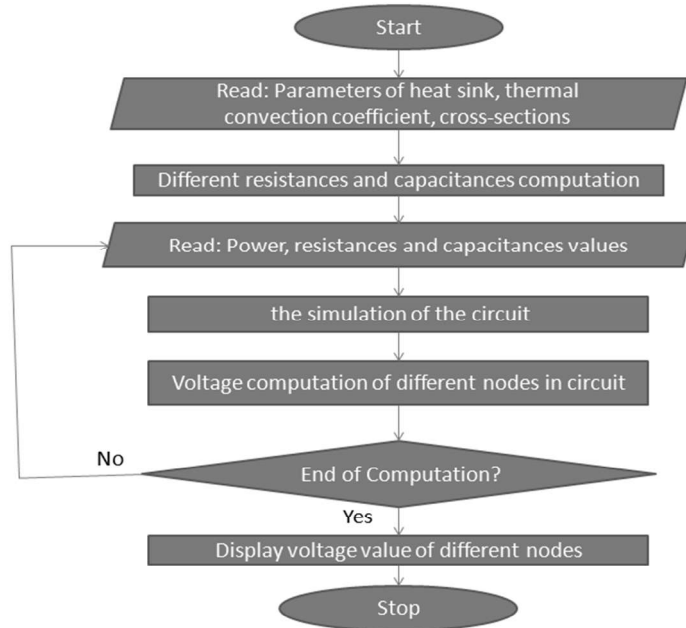

Fig.4. Algorithm of thermal analysis of the system (integrated circuit placed on a heat sink)

4. Evaluation of efficiency of different cooling techniques

In the following section, we perform the temperature computation of two different cooling systems by using our approach, Fig.5. Hence, the first case is composed of an integrated circuit situated at the geometrical centre of a large dimension heat sink made by aluminium that has sixteen heat fins. In the second case the integrated circuit is placed on the geometrical centre of an active fan heat sink, which is the half of the large dimension heat sink attached to a fan. For symmetrical reason Fig.5a and Fig.5b depict the half of heat sink utilized to first and second case respectively. In order to evaluate the effectiveness of both cooling methods, we compare the temperature results obtained from different cooling systems. Table1 contains the parameters of different cooling systems and the ambient temperature was set to 298K (25°C).
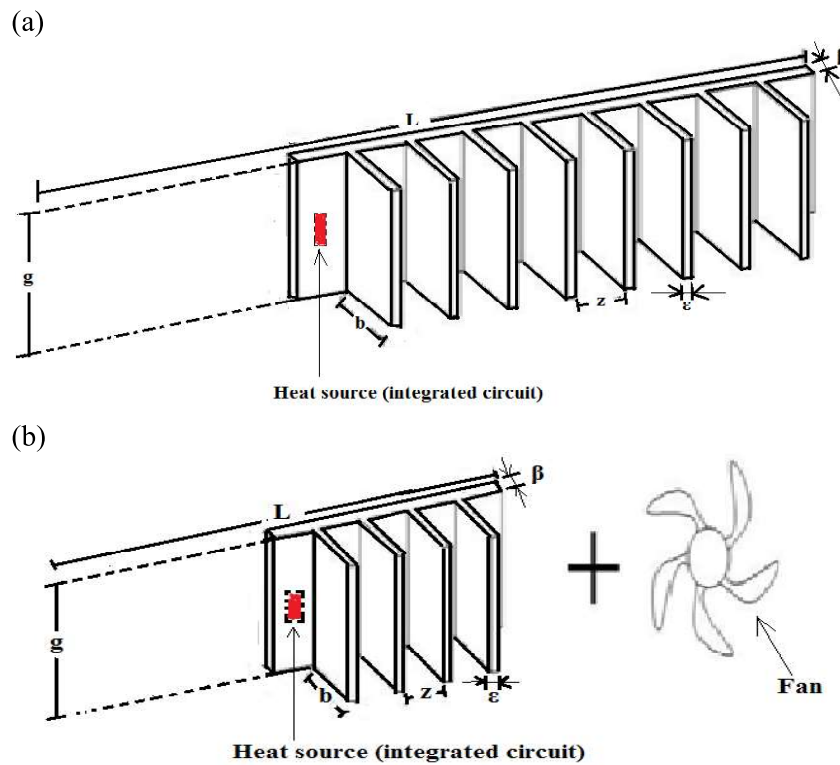
(a)

(b)

Fig.5 (a) large dimension heat sink and (b) active fan heat sink

Table1. Different Parameters of the systems

Name of parameters	Symbol	Values
Heat sink fin thickness	ε	5 mm
Heat sink fin height	b	150 mm
Distance between fins	z	40 mm
Heat sink base width	g	90 mm
Heat sink base length	L	360 mm
Heat sink base thickness	β	10 mm
Conductivity of heat sink	λ	204.2 W $\times$ m$^{-1}\times$ K^{-1}
Convection coefficient	h	Natural convection h=20 W $\times$ m^{-2} $\times$ K^{-1} Forced convection h=40, 60, 80 and 100 W $\times$ m^{-2} $\times$ K^{-1}
Power dissipated by integrated circuit	P	10 W
Density of heat sink	ρ	2707 kg $\times$ m^{-3}
Specific heat of heat sink	c_p	896 J $\times$ kg^{-1} $\times$ K^{-1}

5. Results and discussion

The proposed approach and compact model are used to compute the temperature variation over the surface of parallel plate fin heat sink with U-shape channels. As depicted in Fig. 6 even a small increase of convection coefficient leads to enhancement of cooling system thermal capability. Hence, the presence of active fan improves the heat transfer capability of the system. Both cooling systems used in our investigation have advantages and disadvantages depending on the application domain. Therefore, the large dimension heat sink is heavier, less efficient and bulky, however it doesn't require any extra energy consumption, which is contrary to the active fan heat sink. Thus the application of a fan required extra energy consumption and causes noise. The increase in convection coefficient leads to the small discrepancy between temperature values of different fins, owing to the high heat transfer capability of cooling system (Fig.6b). Hence, the active fan heat sink is more effective than simple large dimension heat sink and requires more mechanical reliability.
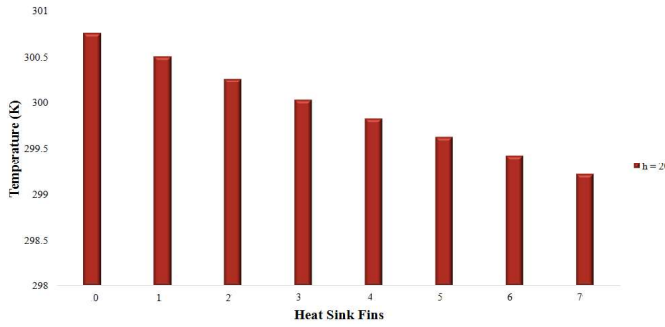
(a)   Passive cooling
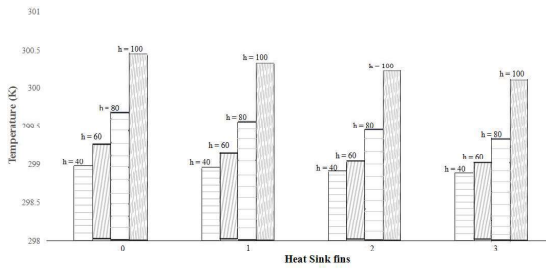
(b) Active cooling

Fig.6. (a) and (b) temperature variation over large dimension heat sink fins and active fan heat sink fins. h - Convection coefficient in $W \times m^{-2} \times K^{-1}$

6. Conclusion

The paper describes the approach, which enables to present the dynamic thermal behaviour of parallel plate fine heat sink with U-shape channels. The proposed approach is based on the analogy between electrical and thermal parameters. Due to that, the transient thermal behaviour of the system may be analysed by using electric simulator program [7]. It might be an engineering solution to perform an adequate thermal analysis and temperature computation of a system in order to assess the cooling system capability. In addition, two different cooling techniques have been compared in order to assess their efficiency. Based on the data obtained from investigation, an increase of forced convection coefficient may considerably improve the cooling efficiency [10].

Finally, the methodology presented in this paper enables modelling of the dynamic thermal behaviour of parallel plate fin heat sink with U-shape channels.

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PORÓWNANIE RÓŻNYCH SYSTEMÓW CHŁODZENIA Z WYKORZYSTANIEM MODELU KOMPAKTOWEGO

Streszczenie

Silny wpływ temperatury na własności układów scalonych wymaga analizy termicznej podczas projektowania konstrukcji modułu scalonego aby zapobiec uszkodzeniom tych układów. W artykule autorzy proponują podejście oparte na kompaktowym modelu RC, które prowadzi do oceny własności dynamicznych oraz wystarczająco dokładnej analizy termicznej w każdym punkcie pomiarowym radiatora z równoległymi płytkami chłodzącymi.

Słowa kluczowe: termiczny model kompaktowy, układ scalony, radiator, temperatura, aktywne chłodzenie