http://dx.doi.org/10.21611/qirt.1998.045

Modelling of conjugate heat transfer in microelectronics with variable fluid and substrate parameters

by B. Więcek

Technical University of Łódź, Institute of Electronics, Computer Thermography Group 18/22 Stefanowskiego St, 90-924 Łódź, Poland, e-mail: wiecek@ck-sg.p.lodz.pl

Abstract

2-D model of heat dissipation in hybrid microelectronic circuits with temperature dependent fluid and substrate parameters is presented in this paper. Natural convection and radiation are included. For natural convection the boundary layer approach is proposed for the as the ceramic substrate vertically mounted with heat source on it. The main result shows the significance of using varying parameters in electronics where the temperature does not exceed the level of 500K.

1. Introduction

Conjugate heat transfer modelling becomes important in thermal design for microelectronics, especially for high-temperature devices, where the temperature of the silicon heat source approaches the level of 500K. The temperature rise over the range of a few hundreds degrees has significant influence on thermal parameters of the air and the microelectronic materials, such as density, viscosity and thermal conductivity [5,7]. To ensure the required accuracy of the modelling, the temperature dependent material parameters should be included. Due to numerical difficulties, multidimensional therm modelling of microelectronic devices with varying parameters is still a problem. We limit our considerations to microelectronic devices that can be modelled by vertical planes with all assumption valid for boundary layer approach [2,6]. This can be easily done for hybrid circuits as the ones shown in figures below.

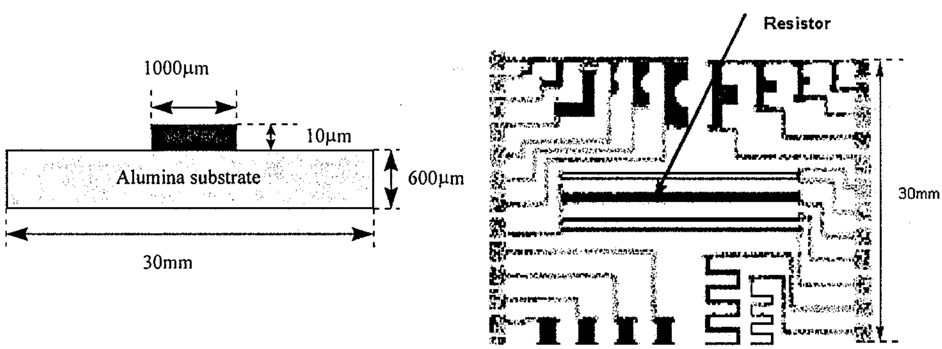

Fig. 1. Hybrid resistor on ceramic substrate

A hybrid long resistor placed on ceramic substrate is the subject of the 2-D modelling. Long here means that the length is much higher that its height, what simplifies the modelling of heat conduction in the substrate. We assume that the energy is being dissipated to the ambient both by natural convection and radiation [3,4]. The aim of this work is to verify if the temperature dependent fluid and substrate parameters in the temperature range 300K-500K are significant for modelling, and what is the quantitative influence of these parameters on the maximum and mean temperatures of the device, and the heat transfer coefficient.

http://dx.doi.org/10.21611/qirt.1998.045

2. Temperature dependent parameters of heat source and ambient

Temperature varying ambient parameters such as: density, viscosity, thermal conductance are included to the modelling. Additionally, in order to ensure a more precise simulation, temperature dependent thermal conductivity of alumina substrate and silicon are considered as well [5,7].

According to Dressler, viscosity, conductivity and density of air can be expressed as:

$$\frac{\mu}{\mu_0} = \frac{\lambda}{\lambda_0} = \left(\frac{T}{T_0}\right)^n \qquad \frac{\rho}{\rho_0} = \frac{T_0}{T} \tag{1}$$

where n=0.68 for gases [2].

According to Sutherland, a more precise approximation of dynamic viscosity of air versus temperature takes a form: [2]:

$$\mu = \mu_0 \frac{T_0 + C_s}{T + C_s}\left(\frac{T}{T_0}\right)^{1.5} \tag{2}$$

where μ_0=18.47kg/(m·s), C_s=115.2K

The diagrams below show how much the significant parameters are non-linear. They have been obtained experimentally for dry air, at a pressure of $p \approx 1000$hPa, [2,7]. Its noticeable that even for microelectronics where the temperature rise is not very high (max. 200K), the parameters change twice or more.

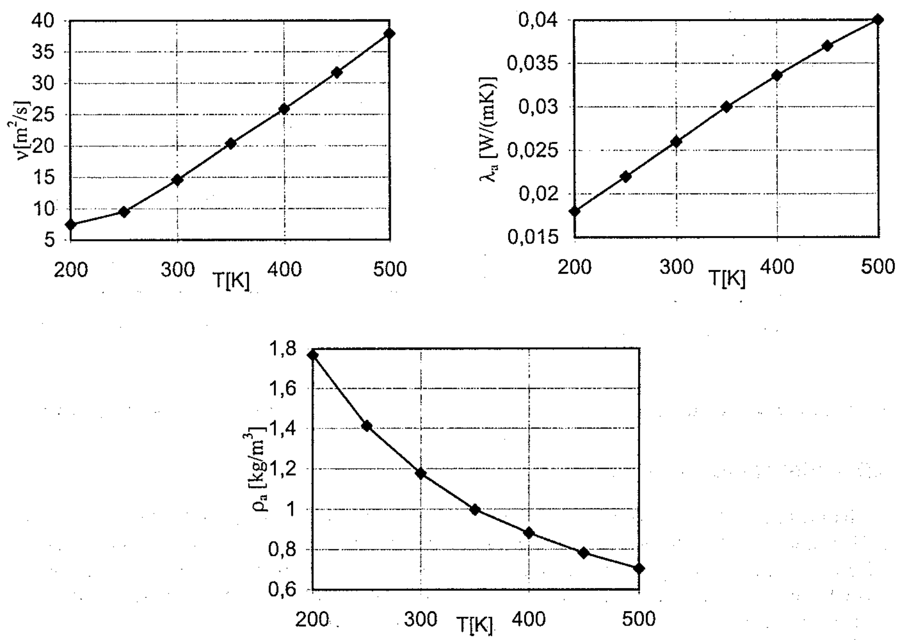

Fig. 2. Kinematic viscosity, density and thermal conductivity of dry air versus temperature (p≈1000hPa) [2], [5], [7]

http://dx.doi.org/10.21611/qirt.1998.045

Approximation of experimental data for air can be expressed by exponential functions suitable for conjugate heat transfer simulation.

$$\lambda_a = 0.026\left(\frac{T}{300}\right)^{0.868}\left[\frac{W}{mK}\right]$$
$$\rho_a = 1.175\left(\frac{T}{300}\right)^{-1.007}\left[\frac{kg}{m^3}\right]$$
$$\mu = 1.83*10^{-5}\left(\frac{T}{300}\right)^{0.756}\left[\frac{Ns}{m^2}\right] \quad (3)$$
$$\nu = 1.55*10^{-5}\left(\frac{T}{300}\right)^{1.765}\left[\frac{m^2}{s}\right]$$

As shown below temperature rise of 200K can decrease the thermal conductivity of alumina and silicon almost 2 times. In practice, it denotes the necessity of including in thermal design and modelling of microelectronic devices the temperature dependent material parameters.

$$\lambda_{Si} = 157\left(\frac{T}{300}\right)^{-1.33}\left[\frac{W}{mK}\right]$$
$$\lambda_{Al_2O_3} = 28\left(\frac{T}{300}\right)^{-1.15}\left[\frac{W}{mK}\right] \quad (4)$$

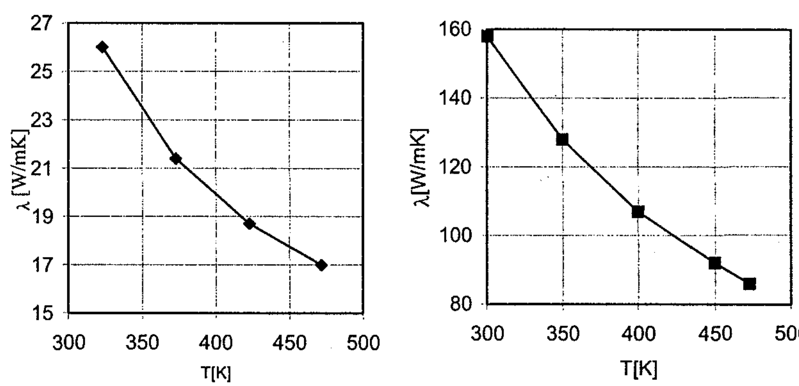

Fig. 3. Thermal conductivity of alumina (left) and silicon (right) versus temperature [5]

3. 2D model of hybrid circuit

Hybrid circuit studied in this work can be modelled using the boundary layer approach. In fact, the ceramic substrate can be treated as a vertical plate. The hybrid resistor, as a long heat source shown in Fig 4, ensures the localised power is dissipated and as a consequence the non-uniform temperature distribution [2,3]. This is a real case for microelectronics where one or more small heat sources are placed on the substrate.

For the case when the resistor is much longer than high, the model of heat conduction in the ceramic substrate can be reduced to single dimension, where the heat dissipates along the x-axes only, see eqn.(5). The model ensures the heat removal from the substrate to the

http://dx.doi.org/10.21611/qirt.1998.045

ambient by natural convection and radiation. Radiation model assumes heat transfer between the hybrid electronic circuit with the emissivity ε and the infinite ambient surrounding the substrate [3].

$$-t_s \frac{\partial}{\partial x}\left(\lambda_s \frac{\partial T}{\partial x}\right) - 2\lambda_a \frac{\partial T}{\partial y} + \varepsilon\sigma\left[\left(T^4 - T^4{}_a\right)\right] = \begin{cases} P_s \\ 0 \end{cases} \tag{5}$$

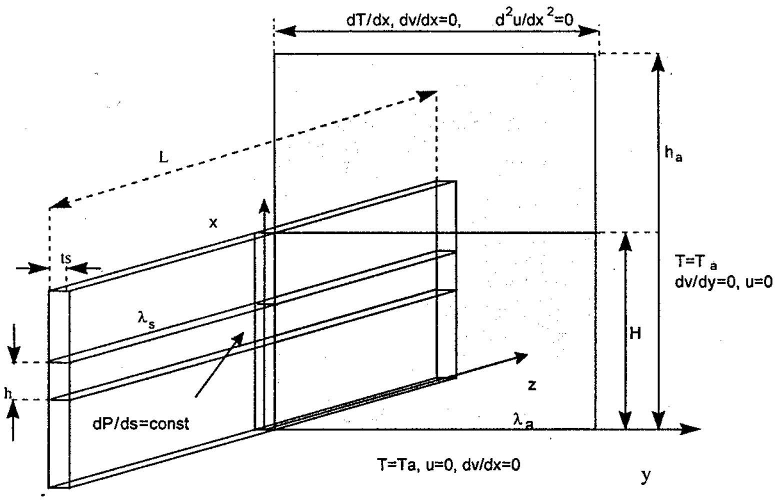

Fig. 4. Geometry of hybrid circuit for modelling including boundary conditions

For natural convection, the boundary layer equations for vertical plate with variable air parameters are used [2], [6].

$$\begin{aligned} &\frac{\partial(\rho_a u)}{\partial x} + \frac{\partial(\rho_a v)}{\partial y} = 0 \\ &\rho_a u \frac{\partial u}{\partial x} + \rho_a v \frac{\partial u}{\partial y} = \frac{\partial}{\partial y}\left(\mu \frac{\partial u}{\partial y}\right) + g\left(\frac{T}{T_a} - 1\right) \\ &\rho_a u \frac{\partial T}{\partial x} + \rho_a v \frac{\partial T}{\partial y} = \frac{\partial}{\partial y}\left(\frac{\lambda_a}{c_a} \frac{\partial u}{\partial y}\right) \end{aligned} \tag{4}$$

The boundary conditions are defined as in the Fig. 4. 2-D conjugate heat transfer model is solved using finite-difference method. 2-D mesh is defined for a rectangular area, and for each mode the software determines values of variables as well as parameters of the air. Then finite differences are used to calculate temperature and velocities.

4. Results

Using the model above described it is possible to obtain the temperature distribution on the substrate, and calculate maximum temperature and heat transfer coefficient. Additionally, one can compare the results with modelling carried out for invariable material parameters, and with thermography validation of the model.

The calculation has been performed for:

Invariant parameters

Temperature varying fluid parameters only

http://dx.doi.org/10.21611/qirt.1998.045

Temperature varying fluid and substrate parameters

Figures below confirm quantitatively a few general conclusions, which could be intuitively drawn. Fluids parameters non-linearity increases the amount of energy dissipated to the ambient. Thermal conductivity of air rising with temperature has the most significant contribution in energy transfer, that as in consequence increases the heat transfer coefficient.

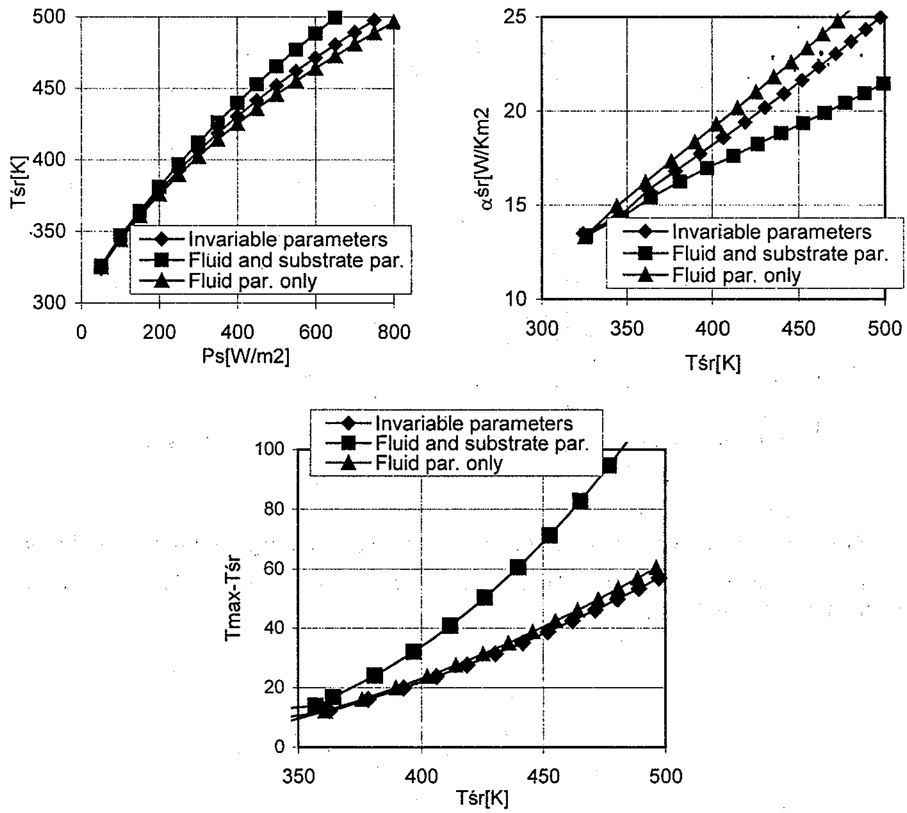

Fig. 5. Results of the simulations, mean temperature versus power, heat transfer coefficient and temperature non-uniformity versus temperature

Larger viscosity for higher temperature compensates the increasing conductivity of air. In addition, the larger the viscosity, the more non-uniform the temperature distribution. The uniformity of temperature distribution can be characterised by the difference between maximum and mean temperature, and it slightly grows with the temperature.

The most significant parameters having a strong impact on the level of energy dissipated is the thermal conductivity of the substrate. Obviously, the larger the conductivity, the more heat is removed. Unfortunately, the thermal conductivity of alumina substrate causes both the decrease of the heat transfer coefficient and enlargement of temperature non-uniformity.

Validation of the model was carried out using thermography. The variation of mean temperature versus power was used for numerical and measured results comparison. This

http://dx.doi.org/10.21611/qirt.1998.045

function is typically non-linear and can be expressed as: $\frac{P_1}{P_0} = \left(\frac{\Delta T_1}{\Delta T_0}\right)^m$. From modelling we got m=1.49, while for measurement m=1.42.

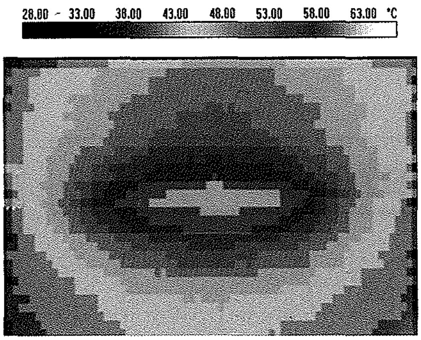

Fig. 6. Nonlinear temperature distribution on the substrate ΔT_{max} =43°C

5. Conclusions

This paper presents 2-D modelling and thermography measurements for conjugate heat transfer of hybrid microelectronic circuit with temperature dependent fluid and substrate parameters. An example of thermal image in shown in this section. The thermography measurements prove the necessity of using variable parameters in the precise modelling.

Obviously, the effects of non-linear parameters are more important at higher temperature. In microelectronics a typical temperature 100K above the ambient is already a temperature for which the variable parameters should be included in modelling. The varying parameters of the substrate are the most significant. They can vary the results of modelling when the temperature of the heat source is about 400K. One can notice that lower values of thermal conductivity of alumina and silicon diminish the amount or energy dissipated to the ambient while the increasing conductivity of air partially compensates it. Lower viscosity of air for the substrate temperature of 500K increases the temperature non-uniformity by 10%. The ideal fluid for microelectronic device should have high conductivity and low viscosity to decrease the temperature gradients. In many practical cases in microelectronics, the uniform temperature on silicon or any other substrate is required.

REFERENCES

[1] KIM (S.) LEE (S.) - *Air Cooling Technology for Electronic Equipment.* CRC Press Inc. 1996, Boca Raton, Florida, USA, ISBN 0-8493-9447-3.

[2] WIŚNIEWSKI (S.) - *Heat Transfer.* PWN, Warszawa 1988, ISBN 83-01-07917-7, in Polish.

[3] WIĘCEK (B.) - *Radiative and convective heat transfer in microelectronics.* Proc. Quantitative Infrared Thermography QIRT'96. Stuttgart, Sept. 2-5, 1996.

[4] WIĘCEK (B.) - *Quantitative approach into the heat transfer by convection in microelectronics with thermography measurements.* Proc. QIRT'96. Stuttgart, Sept. 2-5, 1996.

[5] DEAN (D.) - *Thermal design of Electrinic Ciscuit Boards and Packages.* Electrochemical Pub. Ltd. Essex 1985, ISBN 901150-18-5.

[6] ROGERS (D.) - *Laminar Flow Analysis.* Cambridge University Press WNT, New York 1992, ISBN 0-521-41152-1.

[7] LIDE (D.) - *Handbook of chemistry and physic.* 71st Edition, 1990-1991, CRC Press, USA 1991, ISBN-0-8493-0471-7.