

MONSTR: A Complete Thermal Simulator of Electronic Systems

Vladimir Koval and Igor W. Farmaga
Lviv Polytechnic Institute, S. Banderas St., 12
290646 Lviv, Ukraine

Andrzej J. Strojwas and Steven W. Director
Electrical and Computer Engineering Department, Carnegie Mellon University
5000 Forbes Avenue, Pittsburgh PA 15213, USA

Abstract -- This paper presents a new approach to 3-dimensional thermal simulation of arbitrary electronic systems. This approach is based on the combination of numerical (finite elements and finite differences) and analytical (Fourier series) techniques which are very general and extremely efficient. Complex electronic systems (monolithic IC's, multi-chip modules, including their packaging) can be analyzed in minutes on PC's to produce a detailed temperature distributions within the system structure. The software system, MONSTR, has been developed and applied to several industrial examples. The results of this analysis are directly entered to the circuit simulator, HSPICE, as the actual temperature for each circuit element and thus an integrated electro-thermal simulation is performed.

I. INTRODUCTION

In the process of designing electronic systems (such as monolithic IC's, multi-chip modules - MCM's or hybrid packages) special attention should be paid to the analysis of temperature fields in three-dimensional structures [1-5]. This is necessary due to the ever growing functional complexity and high package density of modern electronic systems that leads to a considerable energy concentration of temperature fields within small volumes, resulting, in turn, in functional faults of these systems. Hence, there is a need to provide a design which satisfies thermal and functional specifications [6-7]. Although there have been many research efforts dealing with the solution of electrothermal analysis problems in electronic systems [1]-[8], there still exists a need to extend these methods to the following problems:

- transient thermal conduction in electronic systems (ES's) and heat exchange with the environment;
- nonuniformity along coordinates of the thermal flow and temperature in boundary conditions;
- 3-D thermal model for multiple layers;
- various boundary conditions at the sides of the structure;
- hierarchical approach to thermal modeling.

Thermal design includes two interrelated tasks:

- analysis of the systems design under the influence of temperature field;
- synthesis of systems under the influence of temperature field.

The analysis of design solutions requires the modeling and investigation of the temperature fields of systems and their influ-

ence on functional parameter. The synthesis of design solutions requires optimum functional and construction parameters which provide certain distribution of temperature fields within a systems.

The thermal simulation problem includes the following tasks:

- analysis of steady-state temperature fields;
- analysis of non-steady-state temperature fields;
- analysis of electronic circuits being influenced by temperature fields;
- analysis of electronics circuits being under external thermal influences;
- analysis of stability and sensitivity of functional parameters under the influence of temperature fields;
- statistical analysis of temperature fields;
- simulation of electronic system reliability under the influence of existing temperature fields.

The role of electrothermal design in a CAD environment is shown in Fig. 1.

The methodology for thermal simulation includes these steps:

- qualitative analysis of electrical circuit, structure and environment of the electronic system;
- developing a thermal model of a system;
- formalizing a mathematical model of temperature field with initial and boundary conditions;
- development or selection of the analysis method for a mathematical model of temperature fields;
- software development;
- the temperature field simulation and analysis.

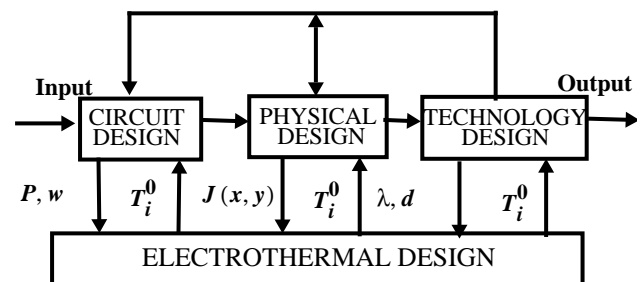


Fig. 1. Role of electrothermal design in CAD.

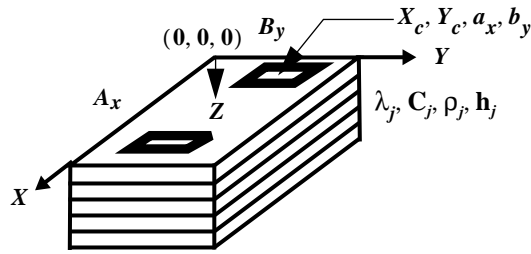


Fig. 2. The general thermal model in the form of a multilayer structure.

This paper presents a brief overview of the comprehensive mathematical approach, and then describes the main features of the software system MONSTR developed for thermal simulation of electronic systems. The capabilities of the system are illustrated by the example of an industrial monolithic integrated circuit from Cherry Semiconductor which had some electro-thermal design problems. We conclude by outlining the main contributions of this work.

II. FORMALIZATION OF THE PROBLEM OF THE ES'S NON-STEADY-STATE TEMPERATURE FIELD SIMULATION

A. Overview of the mathematical approach.

Formalization of the problem of the ES's thermal field simulation is based on the description of the thermal conduction process in the general thermal model (See Fig. 2) with the assumptions about the heat exchange with the environment by the system of initial and boundary conditions. (A_x -is the model dimension along X axis; B_y -is the model dimension along Y axis; X_c -is the heat source center coordinate along X axis; Y_c -is the heat source center coordinate along Y axis; a_x -is the dimension of the heat source element along X axis; b_y -is the dimension of the heat source element along Y axis; h_j -is the j -th layer thickness; λ_j -is the j -th layer thermal-conductivity coefficient; C_j -is the j -th layer specific heat; ρ_j -is the j -th layer specific density).

The fundamental principle of the proposed solution method is based on the decomposition of the original problem into a series of subproblems which allow to obtain analytical solutions at the lowest level and then combination of these solutions into a general one by using the numerical approach.

To formalize the boundary conditions of various types we introduce them in the following form:

$$\Phi[1, S] = T; \quad \Phi[2, S] = \frac{\partial T}{\partial S} \quad (1)$$

$$\Phi[3, S] = \lambda \frac{\partial T}{\partial S} + \alpha_s (T - T_a) \quad (2)$$

where 1,2,3 - denote the type of boundary conditions; S - the value of coordinates, $S \in \{x, y, z\}$; T - temperature; λ - thermal conductivity coefficient; α_s - convective heat transfer coefficient; T_a - the ambient temperature.

B. Mathematical description of thermal model.

Mathematically, the process of transient thermal conductance can be described by the Fourier differential equation for the j -th layer:

$$c_j \rho_j \frac{\partial T^{(j)}}{\partial t} = \lambda_j \left(\frac{\partial^2 T^{(j)}}{\partial x^2} + \frac{\partial^2 T^{(j)}}{\partial y^2} + \frac{\partial^2 T^{(j)}}{\partial z^2} \right) \quad (3)$$

The initial condition has the form:

$$T(x, y, z, 0) = T_a(x, y, z) \quad (4)$$

To obtain unique solution for the entire structure, the particular solutions per layer are combined into a general solution by using the boundary conditions for the adjacent layer for

$T(x, y, z)$ and flows $\lambda \frac{\partial T}{\partial z}$:

$$T^{(j)}(x, y, z_j, t) = T^{(j+1)}(x, y, z_j, t) \quad (5)$$

$$\lambda_j \frac{\partial T^{(j)}}{\partial z} \bigg|_{z=z_j} = \lambda_{(j+1)} \frac{\partial T^{(j+1)}}{\partial z} \bigg|_{z=z_j} \quad (6)$$

III. SOLUTION OF THE THERMAL PROBLEM BY A COMBINED METHOD.

The solution of the problem, which has been formalized above is realized with the help of a specially developed method which is a combination of numerical and analytical methods. These techniques allow us to obtain a generalized solution which makes it possible to analyze both steady-state and transient thermal fields in a multilayer structure with various boundary conditions. The sequence of steps is the following:

A. Reduction of a transient equation to a quasi-steady-state form.

To decrease the dimension of the differential problem and to obtain similar solutions for both transient and steady-state cases we use the method of planes for the initial equation transformation. In particular we use the transverse scheme of the method for the parabolic equation having substituted the time derivative by the left-hand difference relation

$$\frac{\partial T^{(j)}}{\partial t} = \frac{T_{i+1}^{(j)} - T_i^{(j)}}{\tau} \quad (7)$$

where $\tau = t_{i+1} - t_i$, $i = 0, 1, i-1$, resulting in the following equation

$$\frac{c_j \rho_j}{\lambda_j \tau} T_{i+1}^{(j)}(x, y, z, \tau) = \left(\frac{\partial^2 T_{i+1}^{(j)}}{\partial x^2} + \frac{\partial^2 T_{i+1}^{(j)}}{\partial y^2} + \frac{\partial^2 T_{i+1}^{(j)}}{\partial z^2} \right) + Q^{(j)}(x, y, z, \tau) \quad (8)$$

where

$$Q^{(j)}(x, y, z, \tau) = T^{(j)}(x, y, z, \tau) \frac{c_j \rho_j}{\lambda_j \tau} \quad (9)$$

is a nonhomogeneous part of equation (8). Thus, the original problem falls into k boundary problems for the differential equation (8). As the function $T_a(x, y, z)$ is known from the initial condition, the unknown functions $T_k(x, y, z, \tau)$, $k = i+1, K$ can be found sequentially by solving for every value of $k = 1, i$ one differential equation of the form (8) with the same boundary

conditions. For a steady-state case when, $T_{i+1}^{(j)} - T_i^{(j)} = 0$, we get a known Laplace equation.

B. Obtaining the solution in the form of twofold series of eigenfunctions.

The solution to a nonhomogeneous equation (8), according to Steklov theorem, may be presented in the form of a twofold Fourier series in terms of eigenfunctions (ψ_n, ψ_m) of the corresponding homogeneous problem:

$$T_k^{(j)}(x, y, z, \tau) = \sum_{n=0}^{\infty} \sum_{m=0}^{\infty} Z_{nmk}^{(j)}(z, \tau) \psi_n(x) \psi_m(y) \quad (10)$$

The form of eigenfunctions $\psi_n(x), \psi_m(y)$ and eigenvalues a_1, a_2 is obtained by solving ordinary differential equations which have been obtained as a result of separation of variables with the account of the correspondingly assumed boundary conditions

$$\ddot{X} + \alpha_1^2 X = 0 \quad (11)$$

$$\ddot{Y} + \alpha_2^2 Y = 0 \quad (12)$$

The eigenfunctions and eigenvalues obtained as a result of solving the equations (11) and (12). have the following form:

C. Obtaining the recurrence relation for a transient problem

To find $Z_{nmk}^{(j)}(z, i)$ we make a substitution of (10) into (8) and having expanded $Q = (x, y, z, \tau)$ into a series analogous to (10), we find its coefficients. We obtain a nonhomogeneous differential equation of the second order:

$$\ddot{Z}_{nmk}^{(j)} - \gamma^2 Z_{nmk}^{(j)} = a_{nmk}^{(j)}(z) \quad (13)$$

Having solved the equation (13) by the constants variation

method for every n and m at k -th time step we get the recurrence relation for a transient problem.

$Z_{nmk}^{(j)}$ is the solution of the equation (13) obtained in the previous time step. At the first time step ($k = 1, i = 0$), $Z_{nm}^{(j)}$ is determined from the initial condition (4) by its expansion into a series of the form (10) and by finding the coefficients:

$$Z_{nm0}^{(j)}(z, \tau) = \frac{1}{\|\psi_n\|^2 \|\psi_m\|^2} \int_0^A \int_0^B T_a(x, y, z) \psi_n(x) \psi_m(y) dx dy \quad (14)$$

D. Per layer formation of the system of equations.

The general solution of the mathematical model for the thermal conduction in a multilayer structure is obtained in the matrix form, which is formed and solved, proceeding from boundary conditions along Z coordinate. Consider now the formation of the system of equations. At the upper and lower surfaces of the structure the conditions of the 1-st, 2-nd or 3-rd type (homogeneous and nonhomogeneous) (1) and (2) are assigned. Using $2N$ boundary conditions (5) and (6) along Z coordinate (N -the number of layers), we get the $2N \times 2N$ system of equations.

Matrices reflect the heat exchange between the layers and with the medium along Z coordinate in accordance with the assigned boundary conditions. The first row of the matrix shows the type of heat exchange between the upper side and the medium. The second and the third rows and elements show the heat transfer between next structure element according to the hierarchy, or with the lower side and the medium-heat sink. Filling the matrices according to the boundary conditions and solving the system of equations, we form the mathematical model along Z coordinate.

E. The development of the integration procedure.

Now we will describe the integration method along Z coordinate in the expression (13). In the methods presented here it is necessary to have fixed nodes (for example, the trapezoidal formula). The appearance of additional intermediate points results in the increase of the number of calculations. The method of spline-quadratures allows for increase in the accuracy of integration and in decrease of the memory storage. Then

$$\int_a^b f(x) dx = \sum_{i=1}^n \Delta i \frac{f_i + f_{i+1}}{2} - \Delta^3 i \frac{v_i + v_{i+1}}{2} \quad (15)$$

where v_i -coefficients at near second member of spline; f_i, f_{i+1} -are the function value; Δi -is the integration step. Using this integration method we obtain the expression of integration coefficient $Z_{nmk}^{(j)}(z, i)$ along Z coordinate.

F. Approximation and eigenfunctions expansion

Now consider the way of approximating the function $T(x, y, z_N, t)$ to integrate it along X and Y and its further use in the mathematical model. The function of thermal field (distribution) at one of the sides is presented in the form of the two-dimensional finite-element approximation. The domain is discretized into K rectangular finite elements, each being considered in a nor-

malized system of coordinates. Four-node finite elements are used. Then for the i -th element, the function $E(x, y, t)$ is of the form:

$$E_i(x, y, t) = \sum_{\alpha=1}^4 N_{\alpha} E_i^{\alpha}(t) \quad (16)$$

where: E_i^{α} - is the value of the function of a node α of the finite element.

The solution of the problem of thermal conduction in a multi-layer structure by analytical methods has been obtained in the form of multiple trigonometric series. Consequently, it is necessary to get the Fourier series expansion of the function $E(x, y, t)$. The coefficients of the series $E_{nmk}(t)$; $n, m = 0, \infty$ are determined from

$$E_{nmk}^{(j)}(t) = \frac{1}{\|\Psi_n\|^2 \|\Psi_m\|^2} \int_0^{Ax} \int_0^{By} E(x, y, t) \Psi_n(x) \Psi_m(y) dx dy \quad (17)$$

The function $E(x, y, t)$ is represented in a discrete form (16). The formulas for the calculation of integrals in the local system of coordinates are obtained in an analytical form. The above methods of approximating of $T(x, y, z_N, t)$ in 3-D thermal conduction analytical models allow to take into account the irregularity (non-uniformity) of the function distribution in the Dirichlet's boundary condition, to combine analytical and numerical solutions of the thermal conduction problems.

IV. THE THERMAL SIMULATION SYSTEM "MONSTR"

The above solutions techniques of the heat conduction problem were implemented in the steady-state and non-steady-state thermal field simulation system, called MONSTR. The system includes a database, graphical user interface, computation modules and analysis/visualization modules. The database is implemented in a custom developed database manager, which allows for interfaces to other CAD systems. Visualization of the computational results is accomplished via 1-d and 3-d color displays. To increase the information contained in the surfaces being displayed the object rotation and re-coloring have been implemented.

MONSTR is implemented in FORTRAN in two versions: PC and workstations. It is extremely efficient computationally. Most of the practical examples can be computed within few minutes on PC. The workstation version allows for much denser grid and bigger problems to be simulated.

V. ELECTROTHERMAL ANALYSIS: EXPERIMENTAL RESULTS.

The "MONSTR" system described above has been applied to simulate performance of low dropout linear voltage regulator CS-8121 (Cherry Semiconductor Corporation). The VR CS-8121 (block diagram is shown in Fig. 4.) is a 5V precision linear regulator with two microprocessor compatible control functions and protection circuitry included on the chip. The composite NPN-

PNP output pass transistor assures a low dropout voltage (1.2V@1A) without requiring excessive supply current (4mA). When a load resistor is connected to the output of the regulator, the load current increases to a large value and the power dissipation in the pass transistor increases. As a result, die temperature increases and thermal gradients are generated which propagate from the power transistor across the die.

Of course in this situation we have to know the real values of temperature at any points of the structure and the dissipation of thermal field in the substrate for each layer of the structure and support the electrothermal compatibility (coherence) for this IC. The layout of the monolithic VR is shown in Fig. 5.. On the left-hand side of the chip there are: series pass power NPN transistor QN1 (Pdis.= 8.565W), PNP transistor QP2 (Pdis.= 269.5mW) and emitter resistor R1 (Pdis.= 194.4mW). Since transistor QN1 and resistor R1 are partitioned into ten identical parts we described their geometry as seven elements (QN1-1, QN1-2, QN1-3, QN1-4, QN1-5, QN1-6, QN1-7; R1-1, R1-2, R1-3, R1-4, R1-5, R1-6, R1-7) with the dimensions, coordinates of centre and power dissipation. Transistors QP22, QP23, QP24, which are situated very close are combined as one QP22X* which accounts for the sum of power dissipation. The CS-8121 is available in a 5 lead TO-220 package. The IC operates up to a junction temperature (T_j) of 150°C. For developing the accurate thermal model of construction of VR, the structure is represented by four layers, shown in Fig. 3. (solder is 95Pb/5Sn and ambient temperature is assumed to be 25°C).

The results of thermal simulation contain the following information: the real values of temperature for each element (this information can be used as input data for circuit simulation); the values of steady-state temperature field in the chip substrate (we can obtain the temperature field for each layer of structure). Both types of information can be used for layout design. The 3-D distribution of temperature field on the substrate of CS-8121 is shown in Fig. 6. The results obtained show that the maximum value of temperature gradient is on the left side of the chip. The CPU time required for this example was about 2 minutes on a PC. The temperature values for each element (the sections of QN1 transistor and R1 resistor were modelled as individual devices) were then entered to HSPICE and electrical simulation for the voltage regulator was performed. This resulted in updates in the current, and thus power dissipation, values for each segment of these devices and the thermal simulation was then repeated. Naturally, in such a sequence the CPU time was dominated by SPICE simulation.

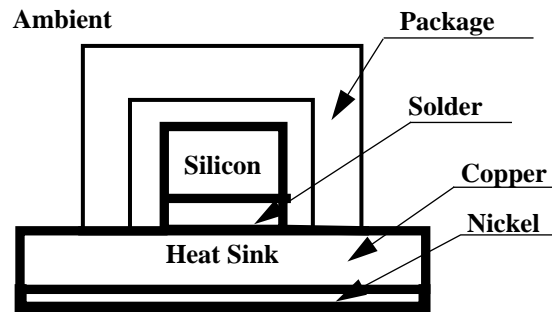


Fig. 3. The structure of voltage regulator CS-8121.

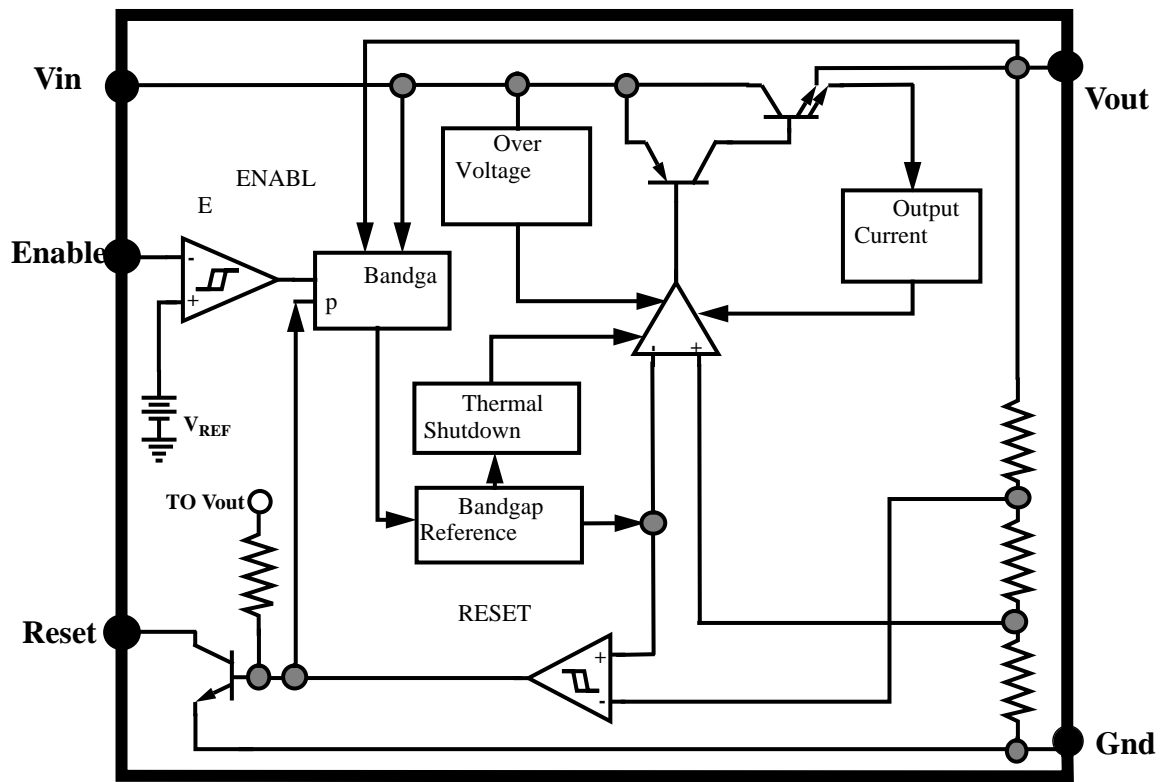


Fig. 4. Block diagram of linear voltage regulator CS-8121.

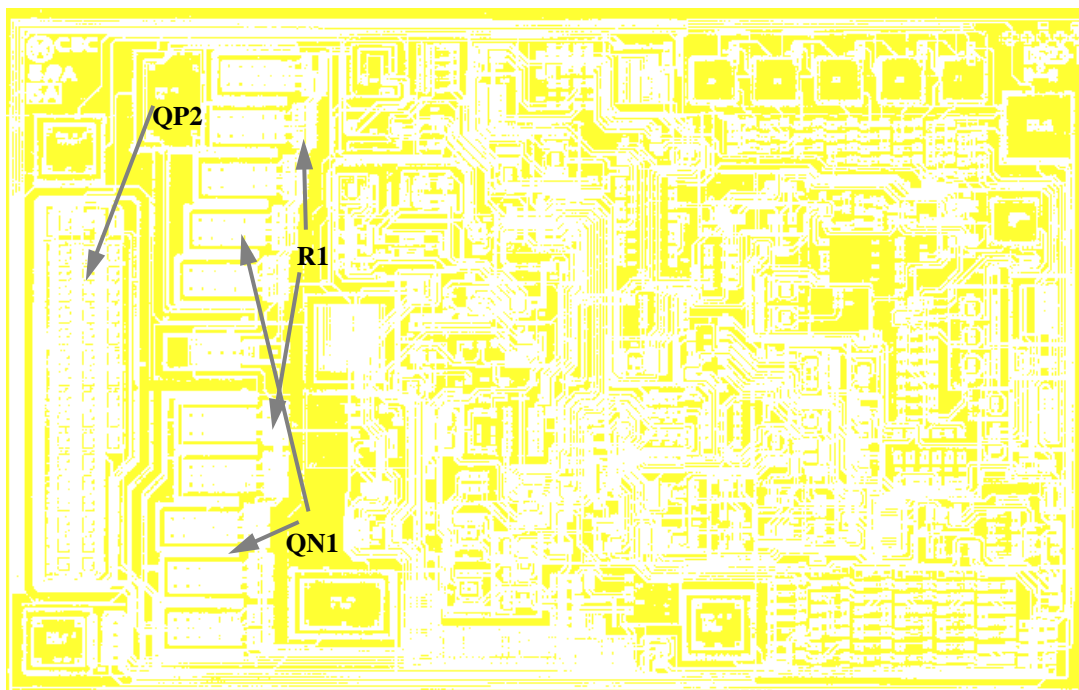


Fig. 5. The layout of voltage regulator CS-8121.

Tmax=67.85°C

Z-axis - Temperature

X
(normalized)

Y (normalized)

Fig. 6. Distribution of the temperature field on the substrate of VR CS-8121.

VI. CONCLUSIONS.

The main contributions of this work can be summarized by the following points:

1. The problem of ES's thermal field analysis has been formalized. Our method of the initial and boundary problem formalization makes it possible to take into account various boundary conditions and apply this analysis in system design.
2. The combination of numerical and analytical methods has been developed for the solution of 3-D parabolic equations. This combination allows for both the steady-state and non-steady-state solutions as well as approximations in boundary conditions along the Z coordinate of the nonhomogeneous functions and their derivatives along the X and Y coordinates.
3. The system "MOSTR" for ES's thermal design has been developed and applied to several practical applications; the system allows for the reduction in the development time and for the improvement in the quality of ES's.

The practical value of the electrothermal simulation methodology presented above lies in the following possibilities: to determine real temperature values at any point of the 3-D structure ES's; to test ES's simulation for conditions of external and internal thermal fields influence and thermal shocks (which replaces the expensive physical experiments); to perform the optimization of parameters by taking into account local temperature values; to calculate temperature tolerances of element parameters; to perform statistical analysis of thermal fields with structural and electrothermal parameter variations.

REFERENCES

- [1] Vladimir A. Koval, Dmitriy V. Fedasyk, Vyicheslav V. Maslov, Vitaliy F. Tarnavsky. The thermal design of micro-electronic systems by CAD tools. Lvov, Ukraine, "Vischa shkola", 1988.-256p.
- [2] Vladimir A. Koval. The models and methods for design manufacturability and functionality of integrated circuits. Lvov, Ukraine, "Vischa shkola", 1985-200p.
- [3] Luc Hebrard, Gilles Jacquemod, Bernard Bouterin and Michel Le Helley. Simulation of electrothermal interactions in power integrated circuits. Proceedings of the eight IEEE SEMI-THERM Symposium, 1992, pp. 76-82.
- [4] Mark A. Kuhlman, Hasan Sehitoglu. A thermal evaluation of multichip module (MCM) materials and designs. Proceedings of the eighth IEEE SEMI-THERM Symposium, 1992, pp. 110-118.
- [5] David W. Snyder. Thermal analysis and modelling of a copper-polyimide thin-film-on silicon multichip module packaging technology. Proceedings of the eighth IEEE SEMI-THERM Symposium, 1992, pp.101-109.
- [6] Leonard W. Schaper. Design of multichip modules. Proceedings of the IEEE, dec. 1992, vol. 80, no. 12, pp.1955-1965.
- [7] John K. Hagge and Russel J. Wagner. High-yield assembly of multichip modules through known-good IC's and effective test strategies. Proceedings of the IEEE, dec. 1992, vol. 80, no. 12, pp. 1965-1995.
- [8] Raj Sullhan, Mike Fredholm, Tom Monaghan, and Anil Agawal. Thermal modeling and analysis of pin grid arrays and multichip modules. Proceedings of the seventh IEEE SEMI-THERM Symposium, 1991, pp.110-116.