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# A new Methodology for Multi-Level Thermal Characterization of Complex Electronic Systems : From Die to Board Level

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## Abstract

*Thermal management is becoming a major concern in microelectronics because of transistor technology reduction and power density increases within complex packages. Temperature rise due to power dissipation worsens harmful clock skew, jeopardizes reliability and leads to over-consumption because of leakage current dependence on temperature. To limit these risks, electronics engineers have to perform thermal simulations at an early stage of the design flow and for several granularity levels (die, package, PCB, ...). To speed up and ease the thermal characterization process, the engineers need small, accurate and easy-to-generate thermal models, which can be reused at every integration step.*

*Several macro-modeling techniques exist (DELPHI, HotSpot, ...), but they cannot satisfy all the points mentioned above. This paper presents a new methodology called Flex-CTM for Flexible Compact Thermal Modeling to build and to interface compact thermal models at different granularity levels. Each part of an electronic system is prepared to be plugged into any other environment and reduced to save memory and time, resulting a thermal micro-model. Therefore, a fast-to-simulate macro-model of a full system can be obtained by assembling the micro-models.*

*The Flex-CTM is found to have number of advantages over both current resistive models (junction-to-case and junction-to-board) and Dynamic Compact Thermal Models. The first advantage of coupling models together allows multi-source and dynamic simulations at any design level. The second is the control on the accuracy. The third advantage is the Boundary Condition Independence property to allow architecture exploration. Finally and the most important, micro and macro-models are shared by teams to be reused and completed.*

Key words: Compact Thermal Modelling, model coupling, package thermal characterization, Boundary Condition Independence, multi-level modelling

## Introduction

In microelectronics, device designers are increasingly miniaturizing the electronic components, to design smaller products and to add new functionalities. This miniaturization is at the origin of a strong rise of the power consumption in electronic systems. Therefore, the transistor technology reduction and the rise of the operating frequency, have caused a dramatic increase of power density in Integrated Circuits (IC). The electro-thermal phenomenon leads to a high temperature elevation with the power consumption increase. Now, the thermal problematic associated with the power consumption becomes a major issue for the microelectronic design, and particularly within the framework of complex circuit design like the System on Chip (SoC) and the System in Package (SiP) circuits.

High temperatures of the components cause thermal and mechanical stresses which affect circuit reliability. The manufacturing cost of the product

increases owing to the need of cooling systems. Furthermore, thermal gradients within the die, due to local hot spots, bring on delay errors in logical gates and thereby limit expected performances. As discussed before, the temperature rise leads to an overconsumption that decreases the autonomy of nomad systems. Moreover, it can lead to a component destruction caused by thermal runaway.

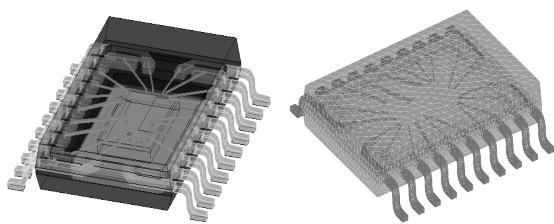
In order to avoid these risks, electronic engineers have to perform transient thermal simulations at an early stage of the design flow, and at several granularity levels (die, package, board). Many teams in a single company are in charge of building their own thermal model (package model, die model, board model...). Consequently, it is difficult to put together the whole set of models to simulate the thermal behavior of a full circuit. The Flex-CTM methodology described here points out the share of these models. The models can be seen as bricks that are assembled to build more complex models.

To speedup the thermal characterization process, the model must be compact and accurate to run fast simulation allowing a bias up to 10%. On the other hand, to cover the entire phenomenon analysis, the models must be dynamic and multi-sources. To summarize the need, a model must meet the following four criteria. First, the models have to be dynamic to cover a large set of phenomena. Second, multiple power sources can be applied to fit with real cases exploration. Third, to save modeling and simulation time, the models must have a reduced number of unknowns. Fourth, to be pluggable and reusable in different use cases, the models have to be boundary condition independent (BCI).

The paper deals with 5 items. First, a short background of existing thermal models is presented. Second, the Flex-CTM methodology is described. Third, the build of elementary pluggable compact thermal models is detailed. Fourth, the modeling and the simulation of the whole system is explained. Finally, the speed and accuracy performances of the methodology are evaluated for a typical integration of systems.

### Background

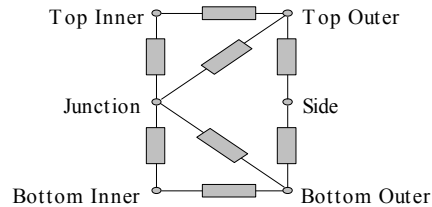
Several models already exist to simulate the thermal behavior of an electronic system. First, numerical methods (Finite Element Method) partition a volume into elementary units. The method transforms the continuous domain into a discrete one in order to compute the temperature at each node of a mesh. According to the JEDEC convention, the numerical thermal model is also called detailed model. These ones may be difficult to build if the geometries are complex. Moreover, these numerical models are huge, then slow to simulate. For example, figure 1 shows the geometry of a complex package and its associated FEM mesh.



**Figure 1: Finite Element Model of a TSSOP Package**

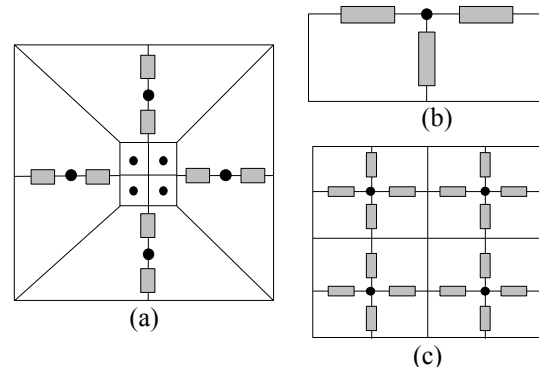
Pioneering DELPHI methodology has been introduced to generate smaller models, in terms of number of unknowns [4]. This is a fitting method that creates Compact Thermal Models (CTM). A CTM is made of a network of resistors between key points of a package (a junction and outers). A DELPHI model is illustrated figure 2. Other fitting methodologies have been introduced to add capacitive terms in the DELPHI compact models

[5], like the European project PROFIT [1] and [6]. The building of these models takes a lot of time because many simulations of the detailed model must be performed in transient domain combining heat transfer coefficients applied on exchange surfaces. In addition, the junction modeling in DELPHI-like models is quite rough because it is considered as a uniform heat dissipation source.



**Figure 2: A Typical DELPHI Compact Thermal Model**

Recently, HotSpot analytical models [2], have been introduced to enhance the thermal model capabilities. The static and dynamic behavior are addressed by a resistive and capacitive network between blocks at different levels. These models are mostly specific for the die. The package and board models are quite coarse and valid for specific heat flux repartitions. Figure 3 shows a resistive HotSpot model of a die divided into 4 blocks on a substrate.



**Figure 3: Resistive HotSpot Model of a Die divided into 4 Blocks on a Substrate**

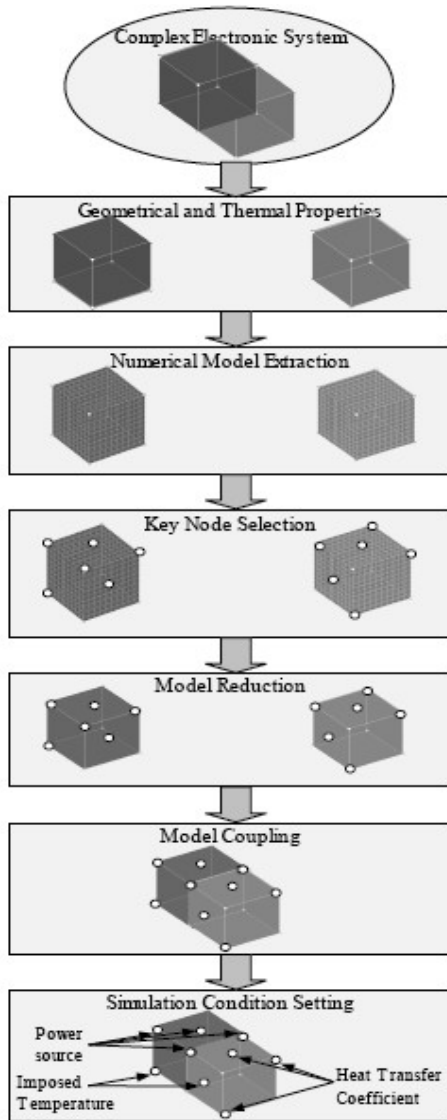
- (a) Connections in the Substrate
- (b) Connections in a block thickness
- (c) Connections on the Junction Surface

None of the existing methods meet all the specifications quoted previously (Introduction section §4). In the following section, a new methodology called Flex-CTM is introduced.

### The Flex-CTM Methodology

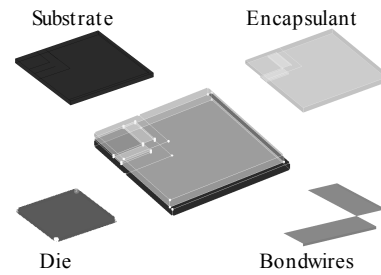
Usually, thermal models are built by different actors at different integration levels and the current methodology does not allow to easily reuse and couple these models. The CTM is “Flexible” in that way it allows to combine models together and to adapt them to any environment. Therefore, the Flex-

CTM methodology relies on the split of the system and processes 6 steps, which are illustrated figure 4.



**Figure 4: The Flex-CTM Methodology**

Firstly, given the geometry and the thermal properties of a global system, a new geometrical and thermal description is created for each homogeneous material part. For instance, a BGA package (figure 5) is split into four descriptions (die, substrate, encapsulant and bondwires). The description contains the interfaces defining the surfaces which allow power dissipation (interface P) and/or heat exchange (interface E). The next 3 stages are applied on each description.



**Figure 5: Geometrical and Physical Description of each part of a BGA package**

Secondly, given the description of a component part, the numerical model is extracted. The numerical model is finely meshed ( $N$  nodes) and built without boundary condition. The results of the extraction are the conduction matrix  $G$ , the diffusion matrix  $C$ , the geometrical properties of all meshing nodes (identifier, matrix index and coordinates), and the nodes identifiers belonging to the interfaces (P, E) of the model.

Thirdly, the huge extracted model has to be prepared before being reduced. The reduction will decrease the size of the numerical system and so, the interface nodes to keep are selected. The whole nodes ( $n_e$ ) of interfaces (P, E) cannot be kept, otherwise the reduction will not operate. To be efficient, the reduction needs the model to verify the rule  $n_e^2 \ll N$ . So, sub-sampled interfaces (P' and E') are defined to substitute for the original interfaces (P and E) in order to reduce the number of external nodes. A trade-off scale between very compact model to very accurate model is available and must be set by the user. That leads to define the subset of external nodes  $n_e'$ . Then, the substituted interface nodes are a function of the original interface nodes following a linear interpolation. The resulting model is given by the numerical model in which selected interfaces (P' and E') are substituted for external interfaces (P and E).

Fourthly, the matrices  $G$  and  $C$  are ordered to place the nodes of respectively J' and E' at the  $n_e'$  first columns. The matrices  $G$  and  $C$  are reduced to decrease the dimension of the system, preserving the first moments orders. The method is called a Moment Order Reduction (MOR) [10]. However, the MOR is enhanced by adding a post-processing that controls the accuracy of the reduction. The reduced model has  $n_e'$  external nodes and  $N'$  unknowns where  $N'$  is approximately 10% of  $N$ .

Fifthly, the micro-models built through the previous four steps are coupled to simulate the thermal behavior of the original system. These micro-models are coupled together through their respective interface nodes. It allows teams to build only their micro-model of interest and to reuse existing ones to model a whole system. The resulting model is called Flex-CTM.

The final step is the setting of the simulation conditions in order to simulate the thermal behavior of the original system. It consists in applying power sources on P' interface, heat transfer coefficients and imposed temperatures on E' interfaces of the Flex-CTM.

Such models meet the specifications because Flex-CTM are small, reused and shared between the different trades. For instance, both package manufacturer and die designer can build their own Flex-CTM and share them to simulate their models in a more realistic environment; against to apply approximative heat transfer coefficients or basic bad-known model. Finally, the Flex-CTM have the "Flexible" property. Meaning that each micro-model of the Flex-CTM can be modified independently.

### Build of Pluggable Compact Thermal Models

The Flex-CTM methodology begins with the creation of micro-models for each part of the whole system. A micro-model is a BCI compact thermal model with external connections for power sources, imposed temperatures, convection models, and other conductive models. This section explains how to build a micro-model.

**Model splitting** is the first stage of the methodology which breaks up the global model into elementary homogeneous material parts. At this stage, the geometries and the physical properties of each part is described. The interfaces of the elementary parts are classified in two groups: power sources (interface P) and exchange interface with the environment (interface E).

Then, the **extraction process** begins with the build of a numerical model of each component of the whole system, without any boundary condition. The meshing of a component is well adapted due to the model splitting step. The finite element method (FEM) is chosen to retrieve the physical transfer functions at any meshing node. The transfer functions between nodes are written as a thermal admittance system. This system conjugates the thermal conductance sub-system  $G$  and the thermal capacitance sub-system  $C$ . The matrices  $G$  and  $C$  are square, symmetric and strictly definite positive. Equation (1) shows the computation of each element of the matrices  $G$  and  $C$  where  $k$  is the thermal conductivity of the material (in  $W.m^{-1}.K^{-1}$ ),  $\rho$  is its density (in  $kg.m^{-3}$ ) and  $C_p$  is its specific heat capacity (in  $J.kg^{-1}.K^{-1}$ ).  $\Omega$  is the volume of the FEM meshing element.  $\alpha_i$  is the form function, which value is equal to 1 on the node  $i$  and 0 on the other nodes.

$$\begin{aligned} G(i, j) &= \iiint k \cdot \text{div}(\alpha_i) \cdot \text{div}(\alpha_j) d\Omega \\ C(i, j) &= \iiint \rho C_p \cdot \alpha_i \alpha_j d\Omega \end{aligned} \quad (1)$$

Moreover, the extraction process gives the geometrical properties of all the meshing nodes.

Each node identifier, index in the FEM matrices and 3D coordinates of the node are extracted. Finally, all the nodes belonging to the interfaces P and E of the model are identified.

The **node selection** step consists in preparing the numerical model before its reduction. To perform it, a subset of external nodes which will be kept after reduction, has to be defined. The external nodes represent the inputs-outputs of the model after reduction. These nodes are used to apply environmental conditions as power sources, imposed temperatures, convection models, and conduction models. The other nodes of the model are called internal nodes. Intuitively, we could define all the surface nodes as external nodes, but it would lead to a very bad reduction. So, the user has to define sub-sampled interfaces which are used in place of the original ones. The number of external nodes on this new interface is  $ne'$ . The user controls the trade-off between accuracy and the size of the reduced model for his study case, modifying the number of external nodes  $ne'$ . The replacement of the original interface by the sub-sampled one is performed through a coupling. This coupling is detailed in the following section ("Whole System Modeling and Simulation").

The **reduction** of a thermal detailed model must be conducted by a robust method because the size of the detailed model is large (few hundred thousand equations). The Model-order reduction (MOR) techniques have been used intensively to reduce drastically the time of the simulations in the thermal analysis. The pioneering method AWE [7] matches the explicitly calculated moments of the system but suffers from numerical instability with higher orders (eg  $>10$ ). Therefore, other methods based on projections on the Krylov subspace have been proposed to reduce the dimension. The most popular methods are the Padé approximation via Lanczos PVL [8], and the well known Arnoldi process of multipoint moment matching approximants of the general discretized thermal system [3], [9], [10]. The Arnoldi algorithm is numerically stable, contrary to the Padé approximation, and the implementation of the Implicitly Restarted Arnoldi Method (IRAM) is available in ARPACK [13].

The discreet expression of the detailed model in time domain has a static member and a dynamic member (2).

$$Gx + C\dot{x} = Bp \quad (2)$$

Where  $G$  is the thermal conductance subsystem,  $x$  the vector of the unknown temperatures,  $C$  the subsystem of thermal capacitances,  $B$  the input-output driver matrix, and  $p$  the vector of the discreet inputs-outputs.

$G$  and  $C$  are sparse and symmetric definite positive of size  $m \times n$ . The vector  $p$  is a dense vector

of size  $m \times n_e$  as well as  $x$ . Where  $n_e$  is the number of external nodes and  $m$  the number of equations.

To reduce the dimension of the system (2) the moment matching procedure will be applied in the frequency domain using the Laplace transformation.

$$\begin{aligned} Y(\omega) &= B^T (G + j\omega C) B \\ \text{if } R &= G^{-1} B \text{ and } A = G^{-1} C \\ \text{then } Y(\omega) &= B^T (I + j\omega A) R \\ \text{and } T(\omega) &= Y^{-1}(\omega) p \end{aligned} \quad (3)$$

Where  $Y$  is the thermal admittance of the system, and  $T$  the vector of the unknown temperatures in the frequency domain.

The matrix  $B$  must be chosen to perform the average of temperatures and the average of power sources according to a set of nodes for each surface, elsewhere it is the identity. Therefore, Arnoldi algorithm is computed on  $A$  and  $R$  to extract the orthogonal bases  $U$  that spans the Krylov subspace.

$$K_{n'}(A, R) = \text{col-span} \{ R, A^{-1}R, \dots, A^{(-n'+1)}R \} \quad (4)$$

Once  $U$  is calculated for a first number of moments ( $n' = n_e + n_i$ ),  $n_i$  starting at 10, the reduction is done by projecting  $G$ ,  $C$  and  $B$  onto the base.

$$\begin{aligned} G'_{n'} &= U^T G U \\ C'_{n'} &= U^T C U \\ B'_{n'} &= U^T B \end{aligned} \quad (5)$$

To control the accuracy, the matrix  $Y'$  of the transfer functions of admittances is calculated (6) in the frequency domain. Note that  $Y'$  is very fast to compute.

$$\begin{aligned} Y'(\omega) &= B'^T (I + j\omega A') R' \\ \text{where } R' &= G'^{-1} B' \text{ and } A' = G'^{-1} C' \end{aligned} \quad (6)$$

While the mean of the  $Y'$  (6) values are changing, (3), (4) then (5) are calculated increasing  $n_i$ . This loop allows to ensure to extract the optimum first order moments that match the Krylov subspace. The reduction rate, comparing the number of values in the detailed system with the reduced system is approximately 90%.

### Whole System Modeling and Simulation

This section deals with the coupling of micro-models to build a model of a full system and then its simulation. The interfaces of the models to connect are not supposed to have the same geometrical configuration. Therefore, the models cannot be coupled by just linking the interface nodes one by one. In the followings, the coupling method to

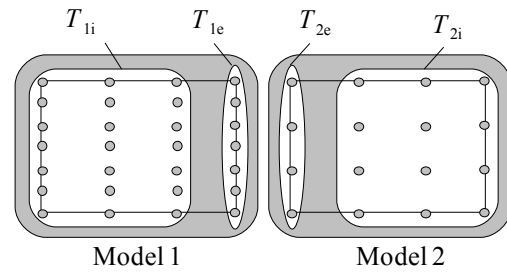
connect two micro-models with different interfaces is described.

Two micro-models ( $G_1, C_1$ ) and ( $G_2, C_2$ ) are assembled in a non-coupled system equation (7).

Where  $G_1$  (resp 2) is the conduction matrix and  $C_1$  (resp 2) the diffusion matrix of the micro-model 1 (resp 2).  $T_1$  (resp 2) is the vector of temperature at each node of the micro-model 1 (resp 2).  $F_1$  (resp 2) is the load vector at each node of the micro-model 1 (resp 2).

$$\begin{bmatrix} C_1 & 0 \\ 0 & C_2 \end{bmatrix} \begin{bmatrix} \dot{T}_1 \\ \dot{T}_2 \end{bmatrix} + \begin{bmatrix} G_1 & 0 \\ 0 & G_2 \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \end{bmatrix} = \begin{bmatrix} F_1 \\ F_2 \end{bmatrix} \quad (7)$$

The repartition of the nodes of the two uncoupled micro-models is described figure 6. The “e” index is for the external node block, and the “i” index is for the internal node block. The structure of the nodes of the two models is modified in order to isolate the external nodes of the model 2, see (8).



**Figure 6: Nodes Repartition of two Uncoupled Models**

$$\begin{aligned} T'_1 &= T_{1e} \cup T_{1i} \cup T_{2i} \\ T'_2 &= T_{2e} \end{aligned} \quad (8)$$

The goal of the coupling process is to create links ( $G_{12}$ ,  $G_{21}$ ,  $C_{12}$ ,  $C_{21}$ ) between two models as shown in equation (9).

$$\begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix} \begin{bmatrix} \dot{T}'_1 \\ \dot{T}'_2 \end{bmatrix} + \begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix} \begin{bmatrix} T'_1 \\ T'_2 \end{bmatrix} = \begin{bmatrix} F'_1 \\ F'_2 \end{bmatrix} \quad (9)$$

with

$$\begin{aligned} G_{11} &= G_1 \cup G_{2i} & G_{22} &= G_{2e} \\ C_{11} &= C_1 \cup C_{2i} & C_{22} &= C_{2e} \\ F'_1 &= F_1 \cup F_{2i} & F'_2 &= F_{2e} \end{aligned} \quad (10)$$

Where  $G_{2i}$  (resp  $C_{2i}$ ,  $F_{2i}$ ) is the internal node sub-block of  $G_2$  (resp  $C_2$ ,  $F_2$ ) and  $G_{2e}$  (resp  $C_{2e}$ ,  $F_{2e}$ ) is the external node sub-block of  $G_2$  (resp  $C_2$ ,  $F_2$ ).

This link is realized by the method of Lagrange multipliers [12], a well known

mathematical method. It transforms a minimization problem under constraints in a minimization problem without constraint. The Lagrange multipliers enable to solve the heat equation (7), ensuring the continuity of temperature at the interfaces of the two models (11).

$$\begin{aligned} \dot{T}'_2 &= X \dot{T}'_1 \\ T'_2 &= X T'_1 \end{aligned} \quad (11)$$

Where  $X$  is the cross coupling between the nodes of the two model interfaces.

This mathematical method applied to the problematic of thermal model coupling is described in [11]. The looking for the singular points of the Lagrangian gives the following matrix system:

$$\begin{bmatrix} C_{11} & C_{12} & -X^T & 0 \\ C_{21} & C_{22} & I & 0 \\ -X & I & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} T'_1 \\ T'_2 \\ \lambda_1 \\ \lambda_2 \end{bmatrix} + \begin{bmatrix} G_{11} & G_{12} & 0 & -X^T \\ G_{21} & G_{22} & 0 & I \\ 0 & 0 & 0 & 0 \\ -X & I & 0 & 0 \end{bmatrix} \begin{bmatrix} T'_1 \\ T'_2 \\ \lambda_1 \\ \lambda_2 \end{bmatrix} = \begin{bmatrix} F'_1 \\ F'_2 \\ 0 \\ 0 \end{bmatrix} \quad (12)$$

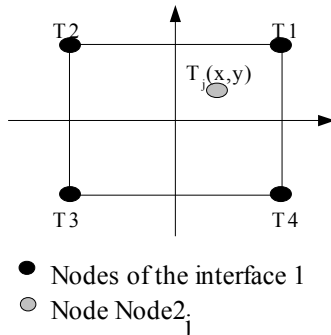
Eliminating  $\lambda_1, \lambda_2$  and  $T'_2$  in (12), it leads to a new equation system (13) which describes the thermal behavior in transient state of the two coupled models.

$$\tilde{C} \dot{T}'_1 + \tilde{G} T'_1 = \tilde{F} \quad (13)$$

where

$$\begin{aligned} \tilde{C} &= C_{11} + X^T C_{21} + C_{12} X + X^T C_{22} X \\ \tilde{G} &= G_{11} + X^T G_{21} + G_{12} X + X^T G_{22} X \\ \tilde{F} &= F'_1 + X^T F'_2 \end{aligned} \quad (14)$$

In this methodology, the coupling matrix  $X$  is an application of the nodes of interface 2 to interface 1. For each node  $\text{Node}_{2j}$  of the eliminated interface 2, surrounding interface-1-nodes are identified (see figure 7).



**Figure 7: Neighbor Nodes Configuration for a Hexahedral Mesh of the Interface 1**

Thus, the neighbor nodes of  $\text{Node}_{2j}$  are weighted, computing the form factors at the coordinates of the node  $\text{Node}_{2j}$ . Equation (15) shows

the general form factors for a hexahedral mesh of first order.

$$\begin{aligned} \alpha_1(x, y) &= \frac{1+x}{2} \frac{1+y}{2} & \alpha_2(x, y) &= \frac{1-x}{2} \frac{1+y}{2} \\ \alpha_3(x, y) &= \frac{1-x}{2} \frac{1-y}{2} & \alpha_4(x, y) &= \frac{1+x}{2} \frac{1-y}{2} \end{aligned} \quad (15)$$

So, the temperature  $T_j$  of the node  $\text{Node}_{2j}$  is computed through equation (16).

$$\begin{aligned} T_j(x, y) &= \alpha_1(x, y) T1 + \alpha_2(x, y) T2 \\ &+ \alpha_3(x, y) T3 + \alpha_4(x, y) T4 \end{aligned} \quad (16)$$

The equation (16) expresses the temperature  $T_j$  as the linear combination  $\Lambda_j$  of the second interface temperatures.

$$T_j = \Lambda_j T'_1 \quad (17)$$

Finally, the coupling matrix  $X$  between the two models is built by all the line matrices  $\Lambda_j$ .

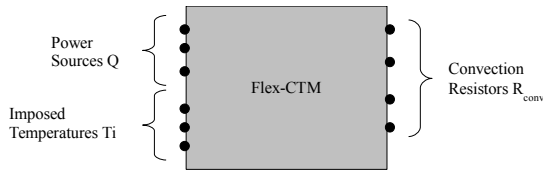
$$X = \begin{bmatrix} \Lambda_1 \\ \Lambda_2 \\ \vdots \\ \Lambda_{ne'_2} \end{bmatrix} \quad (18)$$

Where  $ne'_2$  is the number of external nodes in the model 2.  $X$  is a rectangular matrix of size  $ne'_2 \times (n1 + ni_2)$ , where  $n1$  is the number of nodes of the model 1 and  $ni_2$  is the number of internal nodes of the model 2.

The Flex-CTM resulting from the coupling process is a RC network which can be solved with a basic Spice like transient simulator. Dirichlet conditions are applied on the model, to impose temperatures  $T_i$  on several external nodes of the Flex-CTM. Neumann conditions are applied on the model to impose heat transfer coefficients on surfaces of the system. That leads to plug convection resistors  $R_{conv}$  (19) on the convection surface nodes.

$$R_{conv} = \frac{1}{hS} \quad (19)$$

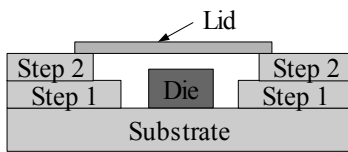
Where  $h$  is the heat transfer coefficient applied on the surface  $S$  of the model. Then, power sources  $Q$  are applied on junction nodes and the Flex-CTM can be simulated in a transient scenario (see figure 8).



**Figure 8: Simulation Condition Application**

### Evaluation of the performances of the Flex-CTM Methodology

The methodology is now evaluated with a simple test case. The studied system is a die in a Ceramic Pin Grid Array (CPGA) package. The geometry of the IC package is described figure 9.



**Figure 9: CPGA Description**

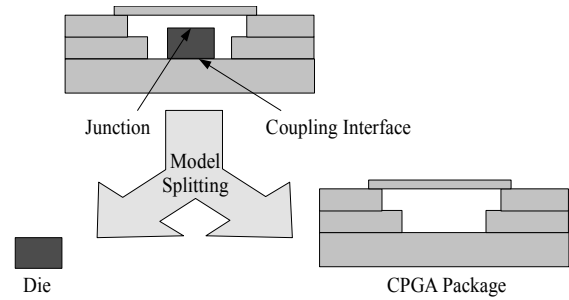
The set of material properties used to model the CPGA package are listed in table 1.

**Table 1: Material Properties of the Different CPGA Parts**

Part	Material	Thermal Conductivity ( $W.m^{-1}.K^{-1}$ )	Volumetric Heat Capacity ( $J.m^{-3}.K^{-1}$ )
Substrate	Typical Alumina	18	3247200
Step 1			
Step 2			
Lid	Kovar	17,5	3704400
Die	Silicon	159.5	1631000

The air layer surrounding the die is assumed to be insulating due to its very weak thermal conductivity. So, in this case a unique die-to-package heat flow path through the bottom face of the die is considered. The CPGA is simulated applying a uniform power source of 1W on the junction surface. The heat transfer coefficients applied on the external package surfaces are computed with a CFD tool. A reference measure of the average temperature on the Die junction is obtained by simulating a FEM model of the full circuit.

The first step of the Flex-CTM methodology splits the CPGA geometry according to the physical properties (see figure 10).



**Figure 10: CPGA Description**

The Junction interface is on the top of the Die and the coupling interface links the Die with the Substrate.

FEM models of both the Die and the CPGA package are extracted to retrieve the numerical systems G and C of both and their FEM node properties. Concerning the heat transfer coefficients, they are simulated with a commercial CFD tool to embed them in the CPGA Package. The nodes belonging to the Junction surface in the Die model, and those belonging to the coupling interface of both models are kept during the reduction process. The FEM Die model has 10 K nodes and the FEM package model has 150 K nodes. The Junction and the coupling interfaces have both 300 nodes. The simulation time of the reference measure takes 4 hours.

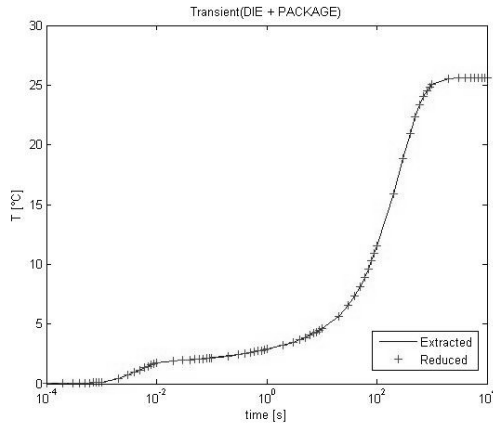
The node selection is performed to keep 64 nodes per interface. This is a medium trade-off between accuracy and complexity.

The reduction method is applied on the two numerical models. After the reduction process, the reduced model of the Die has 168 nodes and the reduced model of the package has 278 nodes. The two reductions take 15 minutes.

Once the two micro-models are available, they are coupled together through the coupling interface and the size of the resulting Flex-CTM is 382 nodes.

Finally, a power step source of 1 W is uniformly distributed on the Junction interface P'. The transient simulation of the Flex-CTM takes 2 seconds. This simulation and the reference are compared figure 11. The maximum of error reaches  $0,1^{\circ}C$  at  $t = 1,5e-4$  s because certain frequencies are smoothed.





**Figure 11: Original Model and Flex-CTM Temperatures**

The comparisons in terms of accuracy, model size and simulation time between the original CPGA and the Flex-CTM are summarized in table 2. The time to build this Flex-CTM is about 25 minutes.

**Table 2: Material Properties of the Different CPGA Parts**

Model	Node Number	Simulation Time
Numerical CPGA model	150000	4 hours
Flex-CTM	382	2 seconds

### Conclusions and Future Work

The Flex-CTM methodology meets the needs of electronic engineers to perform a fast temperature analysis of a complex electronic system at different integration levels. Flexible Compact Thermal Models are BCI, so they can be reused whatever the environment is. Many power sources can be applied on junction nodes allowing hotspot detection on a die. Moreover, Flex-CTM have a few node number, which allows multiple exploration or electro-thermal simulation in a constant window of time. Finally, the methodology enables system designers to share their work at different integration levels.

The methodology has been evaluated with a simple test-case at the package modeling level. The results show that Flex-CTM meet the specifications required specifically in terms of accuracy, and simulation time saving.

The next step is now to enhance the methodology with an automated selection of the number of nodes at the interfaces.

Besides, several test cases covering multi-level (die, package, board) design aspects are to be run.

### References

Articles from conference proceedings

- [1] C. Lasance, "The European Project PROFIT: Prediction of Temperature Gradients Influencing the Quality of Electronic Products", Proceedings of the SEMITHERM XVII, pp. 120 – 125, 2001
- [2] W. Huang, K. Sankaranarayanan R.J. Ribando, M.R. Stan and K. Skadron, "An Improved Block-Based Thermal Model in HotSpot 4.0 with Granularity Considerations", Proceedings of the Workshop on Duplicating, Deconstructing, and Debunking (WDDD), in conjunction with the 34<sup>th</sup> International Symposium on Computer Architecture (ISCA), 2007.
- [3] Hang Li, Pu Liu, Zhenyu Qi, Lingling Jin, Wei Wu, Sheldon X.D.Tan, and Jun Yang, "Efficient Thermal Simulation for RunTime Temperature Tracking and Management", Proceedings of the 2005 International Conference on Computer Design (ICCD'05).

Journal articles

- [4] H. Vinke and C. Lasance, "Compact Models for Accurate Thermal Characterization of Electronic Parts", IEEE Transactions on Components, Packaging and Manufacturing Technology – Part A, Vol. 20, NO. 4, December 1997
- [5] F. Christiaens, B. Vandeveld, E. Beyne, R. Mertens and J. Berghmans, "A Generic Methodology for Deriving Compact Dynamic Thermal Models, Applied to the PSGA Package", IEEE Transactions on Components, Packaging and Manufacturing Technology – Part A, Vol. 21, NO. 4, December 1998
- [6] C. Lasance, "Highlights from the European Thermal Project PROFIT", Journal of Electronic Packaging, Vol 126, pp 565 – 570, December 2004
- [7] L. T. Pillage and R.A. Rohrer, "Asymptotic waveform evaluation for timing analysis," IEEE Transactions CAD, Vol. 9, pp. 352-366, Apr. 1990.
- [8] P. Feldman and R.W. Freund, "Efficient linear circuit analysis by Padé approximation via the Lanczos process," IEEE Transactions. CAD, vol. 17, pp. 645-654, Aug. 1998.
- [9] L. Codecasa, D. D'Amore and P. Maffezzoni, "An Arnoldi Based Thermal Network Reduction Method for Electro-Thermal Analysis", IEEE Transactions on Components and Packaging Technologies, Vol. 26, No. 1, March 2003.
- [10] D. Celso, X. Guo, P. K. Gunupudi, R. Khazaka, D.J. Walkey, T. Smy and M.S. Nakhla, "The Creation of Compact Thermal Models of Electronic Components Using Model Reduction," IEEE Transactions on Advanced Packaging, Vol. 28, No. 2 May 2005.

[11]T. Bechtold, E. B. Rudnyi, M. Graf, A. Hierlemann, J.G. Korvink, "Connecting Heat Transfer Macromodels for MEMS Array Structures", Journal of Mechanics and Microengineering, 15(6), pp 1205 – 1214, 2005

Book

[12]G. Strang, "Introduction to Applied Mathematics", Wellesley Cambridge. Press USA, 1986.

Web sites

[13]Francisco M. Gomes and Danny C. Sorensen,  
<http://www.caam.rice.edu/software/ARPACK/>