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Generation of Compact Thermal Model of a Ball Grid Array Package based on Experimental Data

Magdy ABDELAAL[1], Tayaz FAKHRY[2], Farah MOHAMMADI[3]
[1]Communication & Networks Engineering Department, Prince Sultan University
P.O. Box No. 66833, Rafha Street, Riyadh 11586, Kingdom of Saudi Arabia
[2,3]Department of Electrical and Computer Engineering, Ryerson University
Toronto, ON, M5B 2K3, Canada

Abstract: This paper presents generation of a compact thermal model of a Ball Grid Array (BGA) based on experimental test results obtained from infrared (IR) camera system. The model is optimized so that the steady state and transient thermal behaviors of the package may be predicted with required accuracy. The optimization algorithm is based on Gauss-Newton and Levenberg-Marquardt methods which are well known as a fast and high performance method of multidimensional optimization using MATLAB.

Keywords: Compact Thermal Model, Ball Grid Array (BGA), infrared (IR) camera system, Optimization.

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1. Introduction

More component density in electronic boards, more speed of VLSI circuits and unwillingly more power dissipation of fast electronic devices seem to be bundled together. Dramatic increase of applications of such circuits and devices, urges the thermal analysis and power management studies of such systems a vital design requirement. The amount of dissipated power by the chip is directly related to its temperature which is a crucial parameter in electrical behavior of electronic components, circuit performance, and reliability of the electronic system. Thermal analysis is an important part of modern electronic design thus that enables the designer to calculate the critical thermal variables as key factors in electrical analysis and accurate performance estimation. In general, there are three levels of thermal analysis: component, package or system level. Depending on the level of the design an electronic designer is engaged with, one of these analyzing levels must be chosen that gives out only the sufficient and relevant information about the thermal behavior of the subject of the thermal analysis [1, 2].

In many cases of thermal analysis most of the information provided as the detailed model is unnecessary for the consumer because it includes the thermal characteristics of undesired locations. A smaller model that is capable of calculating only the hot spots, the temperatures and heat fluxes at some desired locations can help the designer to perform the thermal analysis much more easily and quickly with the required accuracy. Such model is called Compact Thermal Model (CTM). CTM can be generated from the detailed numerical model or the experimental data. This paper focuses on generation of CTM at package level using experimental test data.

The key to successful experimental test (for the purpose of thermal analysis) is the ability to obtain comprehensive and accurate prediction of temperature gradients influencing the quality of electronic products under near real-time operating conditions. However, the commonly used method of gathering these temperature gradients using thermocouples is limited by the large number of points to be monitored and the small size of the components being measured. Connecting tens to hundreds of thermocouples is very time consuming. In addition, thermocouples can act as heatsinks and conduct away heat, affecting the accuracy of measurements since the action of the heatsink may lower device temperatures.

Infrared (IR) thermal imaging system is a method which addresses the above-mentioned issues by providing comprehensive two-dimensional temperatures gradients of components under test [3, 4]. This is accomplished without the need to make contact with the components. Therefore, the work focuses on generation of CTM at package level using experimental testing data obtained from infrared thermal imaging system.

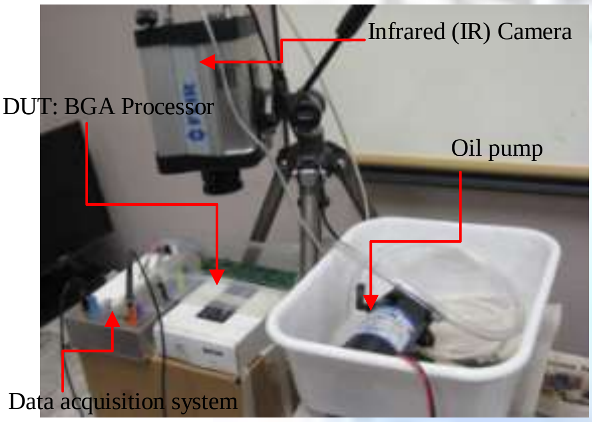
2. Thermal Analysis of Electronic Packages by Infrared (IR) Camera

A recent infrared thermography setup for thermal analysis of electronic packages was proposed by [3] in 2009. The measurement setup is used to perform two types of analysis a) steady state analysis, b) transient analysis. In steady state analysis, after switching the power ON, a time interval is given to the system to reach its steady state condition. This is due to the fact that oil based heat-sink takes some period of time to completely cover the whole surface of the device under test (DUT) and remove the heat homogenously. To perform transient analysis on the DUT, an abnormal stress is imposed to a system in the form of different load work conditions.

The major apparatus used in the proposed experimental setup include an FLIR infrared camera system, data acquisition system, digital thermometer, infrared transparent oil (Aldrich oil), oil pump and power supply. A typical measurement setup is shown in Fig. 1 [3]. The measurement setup is capable of capturing up to 420 frames per second (fps) with a 10µm×10µm spatial resolution, and it can be applied to multiple chips with relative simplicity. The IR camera frame rate can be increased up to 10 KHz as long as the bandwidth of the camera stays under 1GB/s.

2.1 Infrared Camera

The infrared camera used in this measuring setup is a FLIR SC4000 camera (Fig. 1) which is a high-speed, high-resolution, high sensitivity, science-grade infrared camera with Gigabit Ethernet, Camera Link and USB interfaces for maximum flexibility and performance. With a 320 × 256 pixel Indium Antimonide (InSb) detector, the SC4000 camera offers unmatched resolution and thermal sensitivity. An extremely sensitive detector and high speed read out design, provide the camera with extraordinary image quality for the most demanding applications. A typical temperature distribution of a DUT with a cooling fan is shown in Fig. 2. The thermocouple installed under the heat-sink (LO1) indicates temperature of 52.3˚C.



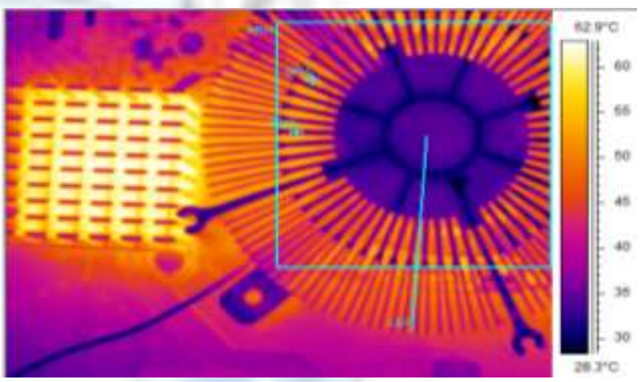


Fig. 1: Typical Test SetupFig. 2: Typical Temperature Distribution of the DUT with Air Cooling.

2.2 Data Acquisition System

The data was captured and analyzed using the integrated data acquisition system of the optical system, supported by PC-based ThermaCAM Researcher software for data acquisition, analysis and reporting. ThermaCAM Researcher software contains powerful measurement and analysis functions for extensive temperature analysis, including isotherms, line profiles, area histograms and image subtraction capability. The acquired input data were recorded in real time for subsequent analysis using this software package. Additionally, the SC4000 camera system has an optional Software Development Kit (SDK) for custom programming and interfacing to the camera.

2.3 Software and computing tools

Various hardware and software pieces are required to obtain a compact thermal model of a package. These tools were applied to the experimental test setup, various coding programs, execution and running the experimental case studies and post-processing analysis.Three different categories of software were applied in this work:

a) ModelSim and Quartus II [5] module is used to run the BGA in a way that the circuitry and as such the BGA, drives a current into the circuit. The static and dynamic compact thermal model may be obtained by calculating the power of the BGA and measuring the junction temperature (the temperature profile of the device under test (DUT) is also available from IR system).

b) ThermaCAM Researcher software for data acquisition (see section 2.2).

c) The last category is mathematical and post-processing software to obtain the compact thermal model for a BGA. An algorithm was developed in MATLAB to calculate the proper values for the RC network. These values are optimized by a cost function and optimization algorithm. The optimization algorithm was based on the Gauss-Newton and Levenberg-Marquardt methods.

3. Parameters for the BGA Test Configuration

Temperature profile were collected from the BGA (CYCLONE II FPGA Development Kit ALTERA, Fig. 3) [6, 7]) using the software development kit (SDK) of the IR camera and Verilog and Quartus II instruction code. Selected parameters for the BGA test configuration is listed in Table 1.

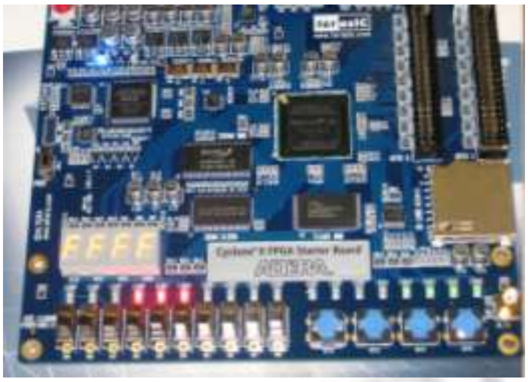


Fig. 3: Device under Test (DUT) - BGA Electronic Package.

Table 1: Parameters for the BGA Test Configuration.

Configuration Parameter	Description
DC Voltage Supplier	7.5 Volts
IR Camera constants: Speed	30 f/s- 2700 frames
IR Camera constants: Pixels	320×256
IR Camera constants: Distance	30 cm
Oil Pump distance	30 cm, identical level
Heat-sink flow	Laminar
Fixed Emissivity	0.92
Average Ambient Temperature	23.3 ˚C

4. Dynamic Compact Thermal Model

Process of generating the compact thermal model for a BGA is illustrated in the flowchart shown in Fig. 4 [8]. First the frames corresponding to the temperature profiles of the surface of the BGA are obtained via the SDK. To perform the procedure of fetching the frames, the software application of Visual C++ was used. This developed program looked for the X and Y coordinates of a specific element (in this case the junction temperature) in a raw data file obtained by SDK. Then a resistor network topology representative of the experimental data was calculated. The transient or time dependent dynamic model of a package is generated by calculating the resistors' and capacitors' value by optimization method.

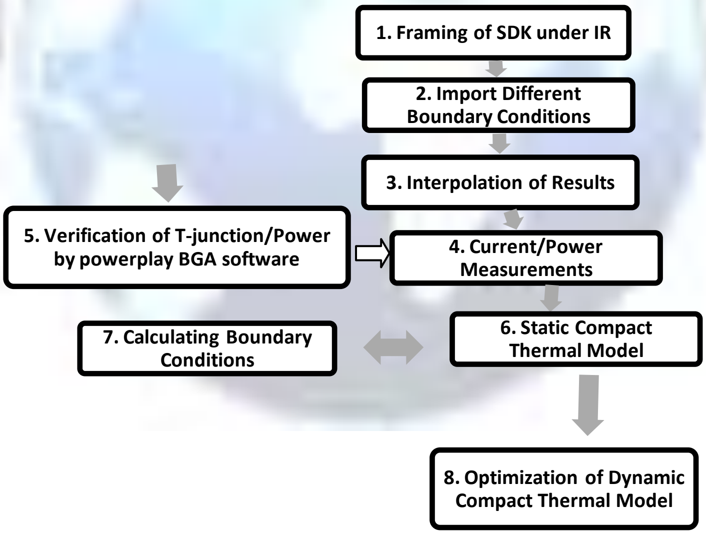


Fig. 4: Flowchart of Generating the Compact Thermal Model for a BGA.

4.1 Definition of a RC Dynamic Compact Thermal Model

The topology of the RC network illustrated in Fig. 5 was used for the BGA package. This RC network includes a total of seven resistors and seven capacitors. Each capacitor represents a particular part of the package thermal mass.
Using node voltage analysis, the governing equation of solving network is [9]:

$$[C]\frac{d}{dt}[T(t)]+[G][T(t)]=[P(t)] \quad (1)$$

where [C] and [G] represent the thermal capacitance and the thermal conductance matrix, respectively.

$[T(t)] = [T_1(t)\ \ T_2(t)\ \ \cdots\ \ T_{14}(t)]^T$ is the temperature vector, and $[P(t)]$ is the nodal loads and sources which express the heat source connected to the junction node and boundary conditions applied to the external nodes.

Equation (1) is a set of 14 linear differential equations. Equation (1) has been transferred from time domain to frequency domain by Fourier transform.

$$[T(\omega)] = (j\omega[C] + [G])^{-1}[P(\omega)] \quad (2)$$

Equation (2) is the definition of the RC network dynamic compact model.

Under steady state conditions all capacitors are fully charged and model is only a resistor network. Therefore, the matrix C is null. The obtained results from detailed model can be used to calculate the matrix G of equation (1). We assume a constant nodal dissipation (p(t)) of 0.25 watts for steady state analysis. For dynamic analysis, power dissipation is a step function with magnitude equal to 0.25 watts.

4.2 Optimization Method

The method of computing resistors and capacitors is performed by an optimization algorithm. An optimization algorithm has been developed in MATLAB [10] to calculate the proper values for these parameters. Their values are optimized by a cost function and optimization algorithm. The optimization algorithm was based on Gauss-Newton and Levenberg-Marquardt methods which are well known as a fast and high performance method of multidimensional optimization. This is one of the most popular and widely used methods of multi-variable or multi-dimensional optimization which belongs to the class of direct search optimization methods (since it doesn't use derivatives of variables). The optimization algorithm tries to find the best values of parameters so a cost function representing the deviation between the compact and experimental test results is minimized. The cost function is defined as:

$$COST = \sum_{i=1}^{N} \sum_{k=1}^{n} \left(\frac{\left|Tj_i^d(\omega_k)\right| - \left|Tj_i^c(\omega_k)\right|}{\left|Tj_i^d(\omega_k)\right|} \right)^2 \quad (3)$$

where N=58 is the number of boundary conditions [11], n=512 is the number of samples in time domain or frequency domain,

$\left|Tj_i^d(\omega_k)\right|$ is the magnitude of the Fourier transform of the ith Junction temperature obtained from experimental test,

$\left|Tj_i^c(\omega_k)\right|$ is the magnitude of the Fourier transform of the ith Junction temperature calculated by compact model.

A summary of the resistors' and capacitors' values of dynamic compact thermal model is listed in Table 2.

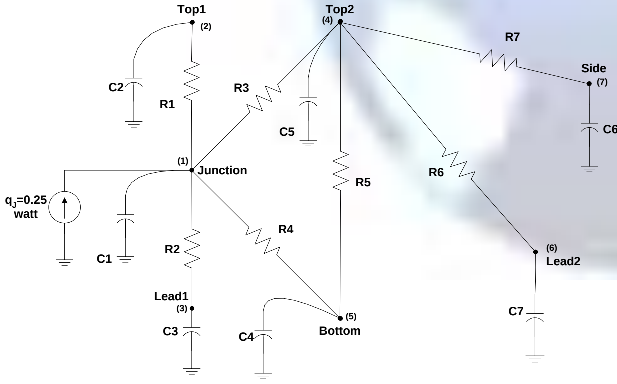


Fig. 5: Dynamic Compact topology for the BGA Package.

Table 2: Static & Dynamic Compact Thermal Models for the BGA Package.

Capacitor – Dynamic Compact Model (J/K)	Resistor – Static Compact Model (K/W)
0.088	54.353
0.026	116.34
1.8057	106.56
0.0015	4.87
0.00042	3.77
0.04	87.70
0.00024	4.39

4.3 Validation

Verification of the compact model is the process of comparing its results to the experimental results and calculating the relative error percentages. According to the criterion proposed in [11] we can consider the generated model *a valid Boundary Condition Independent Compact Thermal Model* if its relative difference with respect to the experimental results does not exceed certain agreed value for predetermined parameters such as junction temperature and heat fluxes. As proposed in [11], the relative errors must not exceed 10% and as long as thermal variables predicted by compact model show relative errors with respect to experimental test less than this predetermined value, the generated compact model is validated and is acceptable.Table 3 shows the junction temperature relative errors for four applied boundary conditions (Case 1:free convection, Case 2: forced convection, Case 3: heat sink, free convection, Case 4: heat sink, forced convection) obtained from dynamic analysis. It's clear that all of the errors are less than 10% criterion accepted in this work.

Table 3: Junction Temperature Comparison.

Case	Compact Model	Experimental Test	Difference
1	41.1	43.9	6.6%
2	37.2	40.1	7.4%
3	32.2	34.8	7.8%
4	24.6	25.7	3%

5. Conclusion

A methodology for generation of static and dynamic compact thermal model using an experimental infrared measurement technique was presented. This method was applied for a Ball Grid Array (BGA). In this work, coupling the IR thermography measurement with the optimization process to generate a compact thermal model was performed. The experimental setup is capable of performing steady state and transient analyses. The optimization process was developed by using an optimization block in order to calculate and optimize the boundary conditions required for the compact thermal modeling. Based on the obtained results, it can be concluded that the dynamic thermal behavior of BGA package can be described by generated dynamic compact model. This model is capable of calculating the temperatures and heat fluxes at some desired locations which can help the designer to perform the thermal analysis much faster and easier with the required accuracy.

Acknowledgement

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