ITM Web of Conferences **48**, 02007 (2022) https://doi.org/10.1051/itmconf/20224802007
ICCWCS 2022

Silicon Die Transient Thermal Peak Prediction Approach

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Abstract. It is well known that Field Programmable Gate Arrays (FPGA) are good platforms for implementing embedded systems because of their configurable nature. However, the temperature of FPGAs is becoming a serious concern. Improvements in manufacturing technology led to increased logic density in integrated circuits as well as higher clock frequencies. As logic density increases, so do power density, which in turn increases the temperature, FPGAs follow the same path. A prediction of the thermal state of the Altera Cyclone V System-on-Chip (SoC) is presented in this work. The prediction study employs a numerical technique called Finite Element Method (FEM), which is a discretization method to approximate the real solution of the Partial Differential Equation (PDE) for heat transfer around the board's critical sources. The DE1 5CSEMA5F31C6N board was simulated using the COMSOL Multiphysics® tool for predicting thermal peaks during 13 hours of normal operation. Using the NISA tool, we obtained very similar results to those previously obtained with a margin of error of 2 %. As a result, a Verilog code implementation that describes the same approach used by the last two simulation tools is uploaded to the FPGA to verify the results of these simulations. This paper provides a more accurate vision of the level of operating stability of our FPGA board, which are currently the most important source for prototyping and designing the world's largest systems.

1 Introduction

With the increase in temperature, Integrated circuits (ICs) leakage power increases exponentially; furthermore, device lifetime decreases exponentially; ICs also operate at a slower speed at high temperatures; therefore, embedded systems based on ICs perform poorly. Additionally, 50 % of all electronic failures are caused by an increase in the internal temperature of the chip [1]. Such as Altera boards (Fig. 1) is devastated if their temperature becomes high [2-3]. All these factors have forced embedded system designers to apply temperature management methods.

Fig. 1. DE1-SoC development board (top view).

Thermal prediction, monitoring, and management are being investigated by researchers across many disciplines. The approaches of these researchers differ from each other in several aspects, including the experimental model used to study the detection and prediction either by modeling and numerical simulation FEM or other methods. Thermal analysis by the finite element method is one of the most efficient numerical simulation methods practiced today. It consists of a simple approximation of the geometry and variables describing the physical phenomenon such as displacement, velocity, pressure, and temperature [4-6]. In the previous works [7], the method of evaluating the thermal peak distributions and temperature distribution of all monitored areas using Gradient Direction Sensor (GDS) is presented along with a method of monitoring the thermal and thermomechanical stress of a Very-Large-Scale Integration (VLSI) chip.
This paper is organized as follows: Section II describes the thermal model of the board and its simulation under COMSOL Multiphysics®. The validation by the NISA tool of the prediction results obtained by the COMSOL tool is detailed in section III. The implementation of a Verilog code that translates the same algorithm used on these last two numerical tools, which is in turn simulated on the NCLaunch Cadence tool, is reported in section IV. Section V concludes the paper by summarizing our main contributions and findings.

2 Simulation of the thermal evolution of the Altera FPGA with COMSOL tool

Figures COMSOL Multiphysics® is a simulation platform that provides fully coupled Multiphysics and single-physics modeling capabilities. However, engineers and scientists use the COMSOL tool to simulate designs, and processes in all areas of engineering, manufacturing, and scientific research [8-11]. In our case, the use of Multiphysics simulation should allow us to gain a deeper understanding of the thermal evolution in a time interval of the Altera Cyclone V FPGA board design. It also represents a design tool thanks to its attitude to managing complex 2D and 3D geometry, and different physical modules existing in COMSOL, among which we find fluid mechanics, electricity, electromagnetism, chemistry, heat transfer, etc. It is possible to combine several physical phenomena in the same numerical simulation, which is the strength of this tool. The global heat transfer equation used in our thermal modeling can be described simply as follows:

$$\frac{\delta \mathbf{T}}{\delta \mathbf{x}}(\mathbf{K_x} * \frac{\delta \mathbf{T}}{\delta \mathbf{x}})+\frac{\delta T}{\delta y}(K_y * \frac{\delta T}{\delta y}) + \frac{\delta T}{\delta z}(K_z * \frac{\delta T}{\delta z}) + P(t) = \rho * \mathbf{C_p} * \frac{\delta \mathbf{T}}{\delta \mathbf{t}} \quad (1)$$

Where Kx, Ky, and Kz are the x, y, and z thermal conductivities, P(t) is the rate at which heat is generated per unit volume, t is time, ρ is the mass density of the material, and Cp is the specific heat. Fig. 2 shows our model of the Altera FPGA board with its four critical zones that generate heat

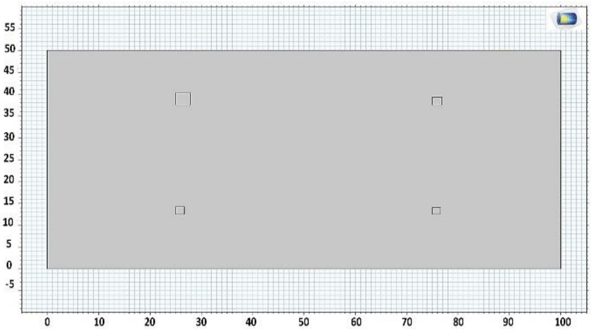

Fig. 2. Modelling the Altera board with the four critical heat sources.

The FEM used must impose simplifying assumptions on the material properties (Table I) and boundary conditions. The finite element method is based on the discretization of space and time. The main advantage of this method is its very high generality, it can deal with complex geometries by considering boundary conditions and temperature-dependent material properties. To solve thermal equations, the boundary conditions must be defined. In our case, we set a constant temperature of 25 °C around the structure of the Altera FPGA board, representing the ambient temperature of the environment where it is placed.

Table 1 : Physical properties of various significant materials.

Material Type	Width (mm)	Depth (mm)	Length (mm)
FR4	6.25	0.3	11.25
Al_2O_3	5.9	0.462	11.6
Gold	5.4	0.038	10.2
Si	5.4	0.13	10.2
SiO_2	9.66	4.86	13.23

Fig. 2 illustrates the modeling of our FPGA board and the four sources of heat that very often generate high temperatures that can damage our circuit and negatively influence the normal operation of the board. This representation is made with different materials that compose them, which are well indicated in Table 1. However, each material has a different thermal conductivity; therefore, this part is essential before we can simulate the thermal model under the COMSOL tool. Fig. 3 shows the thermal evolution of the first simulation of the Altera 5CSEMA5F31C6 FPGA board.

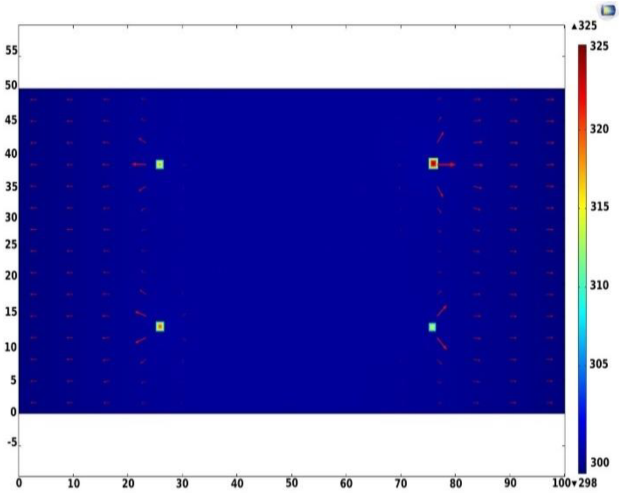

Fig. 3. Thermal distribution of the four critical heat sources on the FPGA board.

This first simulation of our Altera FPGA board under COMSOL gives a good idea of the behavior and thermal diffusion of the heat sources in an FPGA board, and it also shows an unimaginable temperature increase to 325 K (51.85 °C), one of the heat sources in the upper right. It is a thermal peak that was reached after the normal operation of the FPGA board lasted for 13 hours. Fig. 4 shows the thermal evolution of the Altera board versus time.

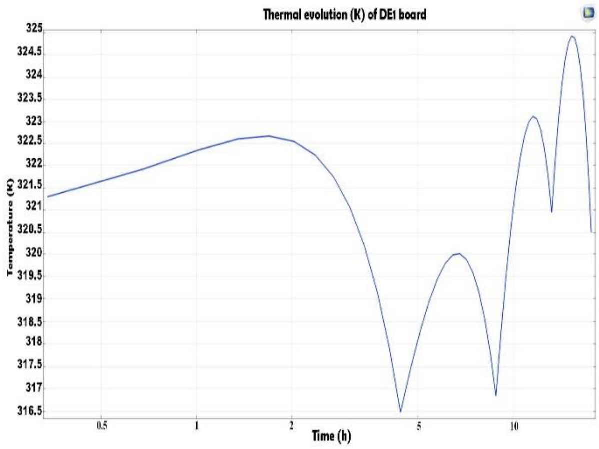

Fig. 4. Thermal evolution of the Altera board versus time.

The graph shown in Fig. 4 is used to clarify the prediction of these thermal peaks and their evolution as a function of time. We can clearly see that after 4 hours of operation of the board, which represented the phase of the transient regime of the FPGA board, we enter the permanent regime or the stationary regime. As indicated, a thermal peak occurs just after 7 hours of ignition of the card, which reaches 320 K (46.85 °C). Then, after around 11 hours of work, another thermal peak is generated, which reaches 323 K (49.85 °C). Next, leaving the card to work well powered, and as soon as it reaches 13 hours of work, another thermal peak is predicted by the COMSOL tool, which can reach 325 K (51.85 °C).

3 Validation of numerical results by the NISA tool

Numerically Integrated System Analysis (NISA) is a finite element-based program that is composed of a series of modules that, depending on the case, have different uses. NISA uses the NISAU/HEAT TRANSFER module, which is a program for the finite element analysis of linear and nonlinear heat transfer in steady and transient conditions [12-16]. In this part, the finite element program NISA is used to predict the thermal behavior of the Altera FPGA board to validate the results obtained by the COMSOL tool, as previously shown.
The approach used with the COMSOL tool is also used with the NISA tool. Fig. 5 shows the results of the thermal evolution of a heat source in the FPGA board. As shown in Fig. 5, the temperature of the heat source on the top right reaches 52.95 °C, which is equivalent to 326.10 K. This confirms and validates the results obtained with the COMSOL tool (Fig. 3).

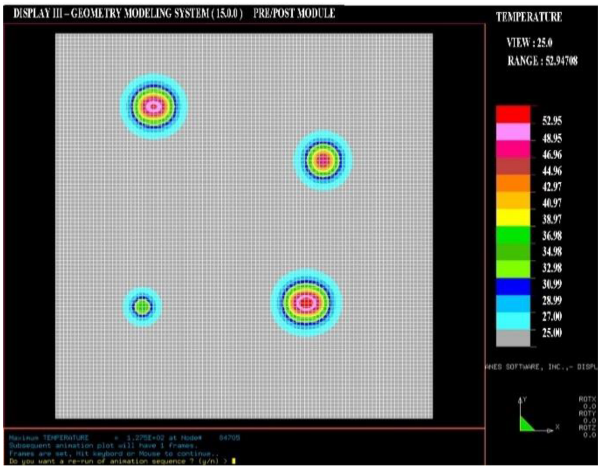

Fig. 5. Thermal distribution in the form of isotherms around a heat source.

This second simulation of our Altera FPGA board with NISA gives a good idea of the behavior and thermal diffusion of the heat sources in the FPGA board.

4 Simulation and FPGA implementation

Recently, the design of specialized applications on FPGAs has been done quickly and efficiently, as they currently play an essential role in the field of rapid prototyping. For this reason, a Verilog code is developed and implemented under the NCLaunch Cadence tool, which is a graphical interface that will allow us to configure and launch the analysis environment to verify and validate the predictions found by COMSOL and NISA. The following part is dedicated to the implementation of the code in the FPGA board under the Altera cyclone V family 5CSEMA5F31C6 platform.

4.1 Logical simulation of the Verilog code

This part has as its main goal the simulation and implementation of the theoretical and numerical results obtained by COMSOL and NISA. For this reason, we have developed a Verilog code.
The examination and validation of the simulation results are realized by the NCLaunch Cadence tool, this last one allows for simulation of the real-time behavior of the system. The implemented Verilog code has been validated against (1) and the study is based on the FEM. Fig. 6 displays the logic simulations showing the equivalent of the results obtained analytically before.

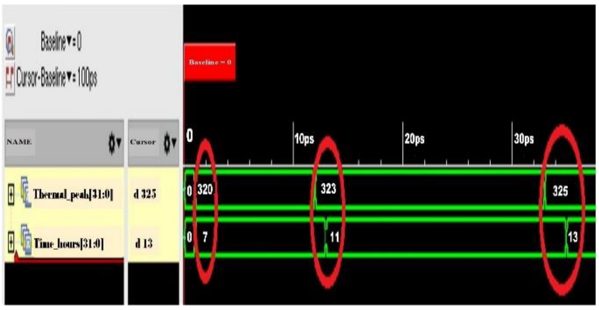

Fig. 6. Results of the thermal simulation with Nclaunch Cadence.

The simulation and synthesis of the heat transfer equation, which is described by the Verilog code, are carried out by the tools of the LIMA laboratory such as the test bench, which verifies the capacity of our algorithm to function according to the initial specifications. The implementation in the FPGA was carried out after the Synthesis Placement and Routing (P&R) steps. Fig. 6 summarizes the results of the three thermal peaks. The most critical one is the one obtained after 13 hours of continuous operation of the board.

4.2 Implementation of the Verilog code on the FPGA board

Once the compilation is complete, after assigning the pins, our program is ready to be uploaded to the DE1 Cyclone V family 5CSEMA5F31C6 board.
Now our Verilog program is available on the Altera DE1 board after setting the clock to 50 Mhz. Fig. 7 shows the value of the critical thermal peak displayed after 13 hours of board operation that is logically simulated and implemented on the FPGA board without floating points. After using the synthesis, planning, placement, and routing tools, the specialized post-synthesis verification tools integrated into the Quartus Prime tool were used to program the FPGA board.
The simulation by the NCLaunch cadence provides us with an insight into the implementation compared to the logic simulation.

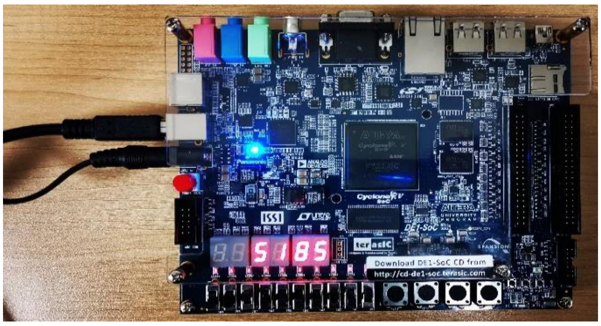

Fig. 7. The value of the thermal peak available on FPGA.

This FPGA implementation clearly shows that the temperature values are almost the same compared to the two simulation results via the two tools COMSOL and NISA. The maximum error is about 2 %, which indicates a good result for the validation of our proposal.

5 Conclusion

In this paper, we have developed a simple 2D model for a rapid heat flow analysis of the Altera Cyclone V board. We have also presented COMSOL and NISA simulations for the prediction of thermal peaks occurring on the board under standard working conditions. A maximum error of 2 % was observed between measured and simulated temperatures. This step is important because it affects the overall performance of the board, and it is for the first time that a practical implementation on this type of board of this simple analysis is carried out to have a clear idea of the thermal diffusion around the four sources that produce the critical heat and that can damage the normal operation of the board if exceeded.

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