Paper

Multi-Domain Modeling and Simulations of the Heterogeneous Systems

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Abstract—This paper discusses the multi-domain modeling and simulation issues of the design and analysis of heterogeneous integrated systems. Modeling and simulation methodology and tools are also discussed.

Keywords*—*Corona, Coventor, 3D integration, e-Cubes, heterogeneous systems, MATLAB, modeling, simulation.

1. Introduction

There is a strong demand in the market for fast and cheap development of reliable, standalone, wireless, multifunctional devices for automotive, aerospace and biomedical applications. Therefore the complexity of electronic sensors and multifunctional devices increases.

Fast development of device fabrication technology stimulates new challenging technology development and progress in wafer processing, module interconnects and packaging technology. Apart from a broad hardware experience, standalone software design simulations have to be done before hardware fabrication.

Such research and development work is done within the framework of e-Cubes [1] and SE2A [2] projects, where multimodule 3D integration of multifunctional elements is the main goal. Many various functionalities, such as power supply, power management, RF communication, digital signal processing, memory, micro electro-mechanical systems (MEMS) and many other have to be assembled into a single device. The range of applications is not limited to automotive, aerospace and biomedical domains only.

As the device integration is an important factor of the design process in improving the reliability of the device, new materials, technologies and technological concepts are being tested and verified. The reliability of vertical interconnects turns out to be one of crucial design issues. Thermal management of the device and thermo-mechanical stress simulations are prime candidates for research on reliability. From the reliability point of view standalone functional module simulations are insufficient to find out whether the modules will work if assembled into a final stacked device or not due to some thermal interactions neglected during the design verification process. For example, if one module dissipates the power, the heat flows through VIA's. It extends to other modules and affects thermal budget of other devices.

A slightly different point of view is exploited within the Corona project [3], where the main goal is to develop the best methodology and tools for fast product development. It should cover the whole flow from the idea to the final micro-nanotechnology product. The key issue is short time-to-market and efficient dataflow for distributed design and fabrication scenarios. One of the main goals of the Corona is also the support of the multi-site product development – where every module of the integrated microsystem may be fabricated in the best technology in different places/fabs and finally integrated into one multifunctional device (Fig. 1).

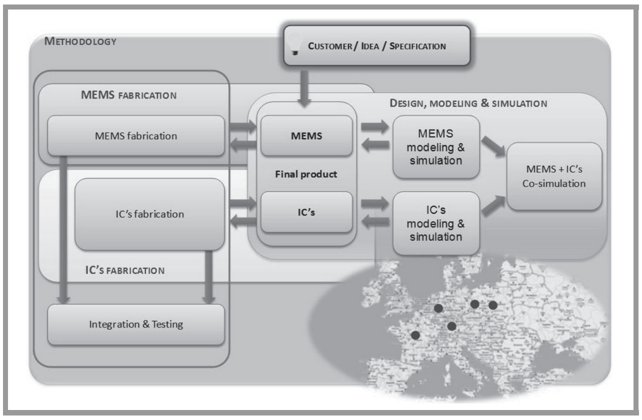

Fig. 1. Multi-site product development scenario, where every module of the integrated microsystem (MEMS+IC's) may be fabricated in the best technology in different places/fabs and finally integrated into one multifunctional device.

From this point of view different design tools are important at different design stages: from device design, through device modeling and simulation, to process development and optimization. It enables fast virtual prototyping for selected parts of the device or the whole final device.

2. Multi-Domain Modeling and Simulation Examples

As it has been mentioned before, multi-domain modeling and simulation is very important at every stage of device fabrication. Selected examples of various multi-domain modeling and simulation are presented.

For design, modeling and simulations of heterogeneous micro- and nanostructures designers may use CoventorWare [4] and ESI-CFD [5] software environments implementing multi-domain FEM (finite element method) simulation and analysis of the micro- and nanostructures. One of the key reliability issues of 3D structures is the interconnection reliability. Several integration techniques have been considered within the framework of the e-Cubes project to obtain sample demonstrator structures. An example of the integrated modeling and simulation is shown in Fig. 2.

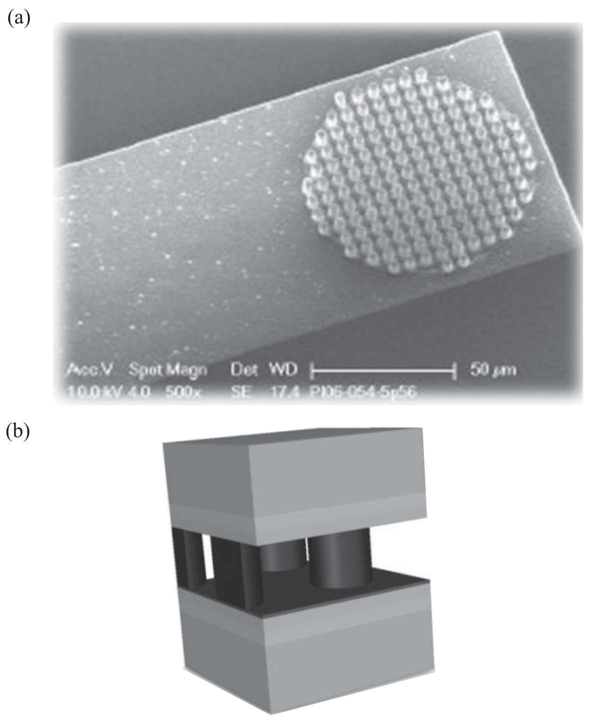

Fig. 2. (a) SEM image of a group of microinserts [6], [7] and (b) 3D model of a quarter of a group of 9 microinserts in CoventorWare.

Thermo-electro-mechanical microinsert simulations [6], [7] have been performed (Figs. 3 and 4) to find the electrical and mechanical behavior of the simulated structures and to verify possible electromigration problems and assess the electrical suitability of the examined structures. The pressure needed to be applied for thermo-compression bonding is also investigated.

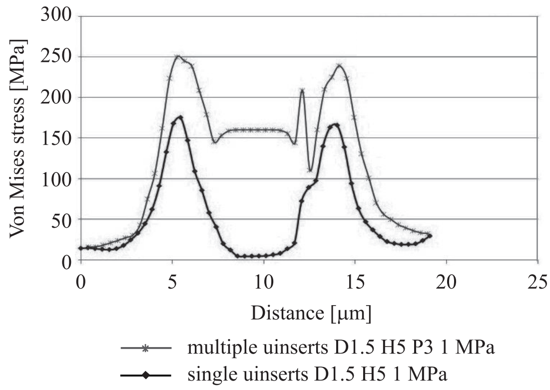

Fig. 3. Multi-domain simulation results: von Mises stress distribution across a microinsert structure under pressure of 1 MPa applied on top of the structure with single and multiple microinsert configurations (diameter of 1.5 m, height of 5 μm and pitch of 3 μm for multiple microinserts).

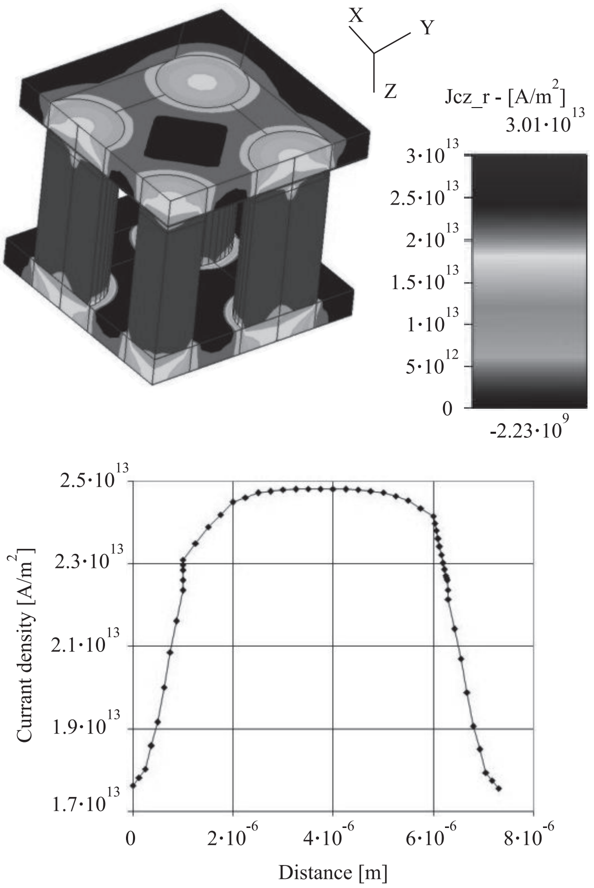

Fig. 4. Multi-domain simulation results: current density distribution through microinserts under 10 V applied between upper and bottom part.

The results presented in Figs. 3 and 4 show the von Mises stress distribution across the microinsert structure under the pressure of 1 MPa for device configurations with single and multiple microinserts. It is very important to characterize the stress distribution under different pressures according to thermo-compression bonding process usually used for 3D integration. The current density distribution shows how the current flows through the modeled 3D device. It also makes it possible to verify if one should expect such problems as, e.g., electromigration. Modeling and simulation results at this stage can help to optimize, e.g., geometry, materials and dimensions (e.g., diameter, pitch, height).

Besides modeling and simulation efforts devoted to the single structure used for 3D integration, modeling and simulation of the integrated microsystem have been also presented. Such a system is the e-Cubes project demonstrator sample. The general idea of the project is presented in Fig. 5 [8].

From the reliability point of view thermo-mechanical behavior of the whole system is one of the most important

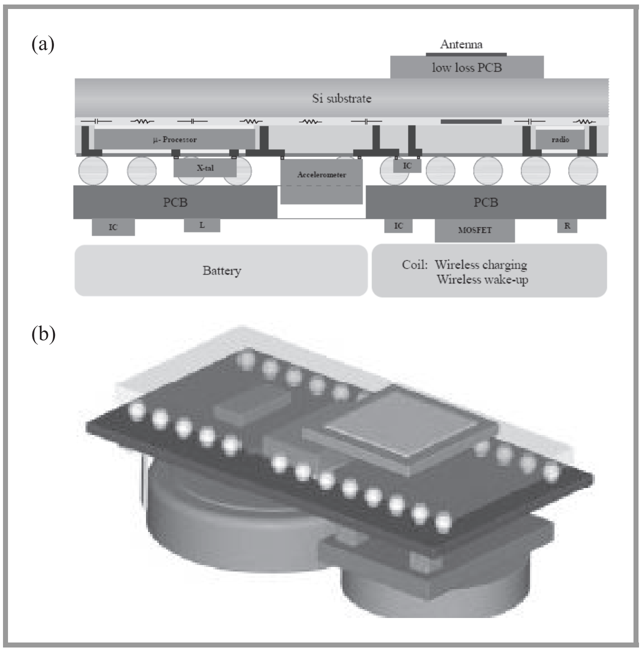

Fig. 5. (a) Physical architecture of a sensor node (whole system for health monitoring), drawing not on scale [8] and (b) mechanical design drawing (3D model) [8].

reliability parameters. Even if all standalone modules are correctly designed, simulated and one can anticipate perfect operation after assembly process, in the case of 3D integration their functionality may be affected by various side effects not taken into consideration during the design process. Each of the assembled modules of a 3D multi-module device interferes thermally and electrically with its neighborhood (see Fig. 6). The probability that a single module may affect another by, e.g., high temperature transfer is quite high. Therefore the module arrangement and complex simulation are necessary at each design stage.

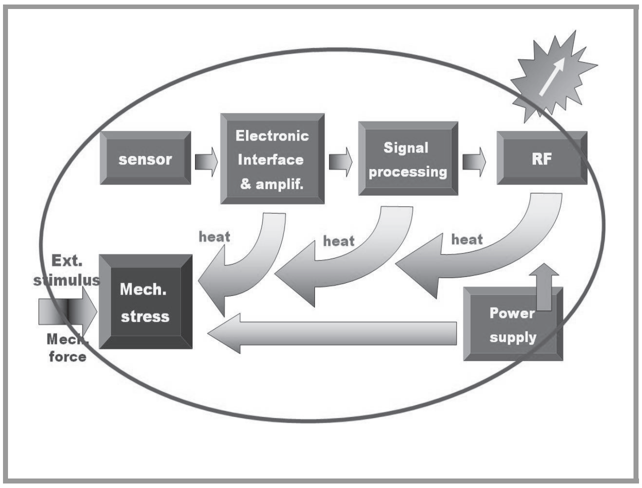

Fig. 6. Interactions between microsystem modules [9].

The 3D integration technique has been simulated along with realistic thermo-mechanical boundary conditions applied (power dissipation from different modules and parts).

Also some mechanical issues regarding the encapsulation methodology were considered. Thermal simulations results show that under the assumed boundary conditions the temperature does not increase too much across the whole demonstrator device structure. Sample results of the thermal investigation are shown in Fig. 7.

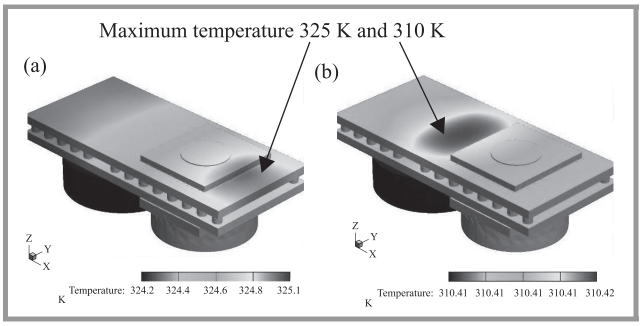

Fig. 7. Temperature distribution through a 3D model of the integrated microsystem in two modes: (a) high power mode and (b) low power mode.

Analysis of the mechanical displacement simulation leads to a major conclusion. Displacement and stress distribution is better if more fixed points are applied to the device (Fig. 8). While in the high power mode the maximum displacement reaches 24 μm on the edge of the structure, in the low power mode the displacement does not exceed 6 μm.

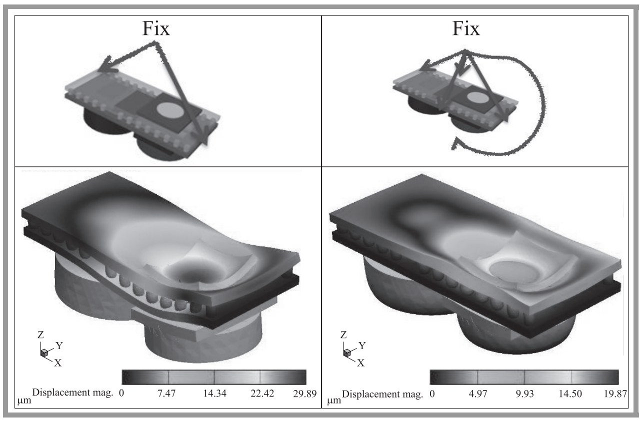

Fig. 8. Mechanical part of multi-domain simulation and modeling results – displacement magnitude (displacement and deformation factor rescaled ×100!!!) of structures in high power mode in two different modes of fixation to the package.

The heterogeneous device oriented (Hedoris) multi-domain simulation system [10], [11] will be developed within the framework of the projects mentioned above. The Hedoris system implements the idea of the hardware description language (HDL) of the device model based on Verilog-AMS [12] language specification used for device thermal modeling. Currently the system is mainly optimized to run thermal simulations of heterogeneous devices and is still under development. Intensive work has been undertaken including TCAD simulations oriented on the system extension to cover thermo-mechanical internal device interactions, such as mechanical stress, which may affect the overall performance of the device.

3. Summary

The design and verification methodologies are discussed and presented. Modeling and simulation samples presented in this paper show the importance of the flexibility of the multi-site design and development framework of cooperation. The paper also shows how universal CAD tools used for design of micro- and nanodevices in distributed engineering environments should be and how important it is to correctly estimate the device reliability and keep balance between reaching the attractive time to market and fulfilling the customer requirements.

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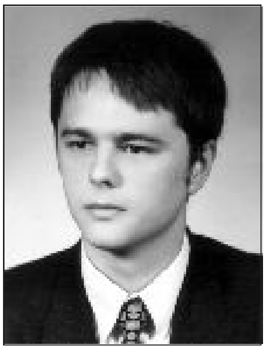

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