3D/TSV Enabling Technologies for SOC/NOC: Modeling and Design Challenges

Khaled Salah
Mentor Graphics
Cairo, Egypt.

Khaled_mohamed@mentor.com

Alaa El Rouby
Mentor Graphics
Cairo, Egypt.

Alaa_El-Rouby@mentor.com

Hani Ragai
Ain-Shams University
Cairo, Egypt.

hfragai@ieee.org

Yehea Ismail
Nile University
Cairo, Egypt.

yismail@nileuniversity.edu.eg

Abstract—According to the International Technology Roadmap for Semiconductors (ITRS), the traditional scaling will no longer meet the performance and integration requirements of systems-on-chip (SoC) in the long term. Therefore, new I/O and packaging paradigms are needed. Three-dimensional integration is a promising alternative option to traditional 2D planar chips. 3D integration is mainly restricted by the communication infrastructure between different stacked dies of future multi-core SoC and network-on-chip (NoC). Among several 3D integration technologies, the TSV (Through-Silicon-Via) approach is the most promising one and therefore is the focus of the majority of 3D integration R&D activities. However, there are challenges that should be overcome before the production of TSV-based 3D ICs becomes possible, e.g., electrical modeling challenges, thermal and power challenges, technological challenges, design methodology challenges and CAD tool development challenges.

Index Terms— Three-Dimensional ICs, Through Silicon Via, Modeling, TSV, Macro-Modeling, Challenges.

I. INTRODUCTION AND BACKGROUND

Increasing drive for the integration of different signals (analog, digital, RF) and technologies (SOI, HBTs, GaAs, strained silicon, and so on) is introducing various design concepts, for which existing planar (2D) technologies may not be suitable, so, three-dimensional (3D) integrated circuits are introduced. A qualitative comparison regarding the benefits introduced by the 3D integration process, compared to existing system design approaches is summarized in Table I. 3D integration technology provides increased performance in many design criteria as compared to the current 2D approaches, as 3D-ICs, which contain multiple layers of active devices, extensively utilize the vertical dimension to connect components and are expected to address interconnect delay related problems (In planar (2D) technologies, scaling is reducing gate delays but also increasing interconnect ones and this will be mitigated by the use of short wires in 3D designs, as schematically shown in Fig.1. These shorter wires will decrease the average load capacitance and resistance and decrease the number of repeaters which are needed to regenerate signal on long wires) and to enable integration of heterogeneous technologies (in the 3D design, a 2D chip is divided into a number of different blocks, and each one is placed on a separate layer of silicon where each layer is stacked on top of each other, as schematically shown in Fig.2. This may be exploited to build SoC by placing different

circuits with performance requirements in different layers which enables novel “More than Moore” applications [1,2].

In 3-D integration, the communication among the stacked ICs and embedded components requires vertical interconnections. Since processing the vertical interconnections is challenging compared to the planar ones, the electrical and mechanical characteristics of the vertical interconnections can be a bottleneck for achieving the required system performance. Thus, various types of vertical interconnections are still being proposed. Several interconnection elements are already popular in industry. Fig.3 shows typical 3D structures with four types of interconnections, including bonding wires, TSV interconnections (which is a new silicon-based 3-D packaging structure), metal bumps and contactless communication. Table II summarizes the main difference between those four types of interconnects. It is clear that to improve electrical performance, TSV interconnections are becoming a major choice to replace the bonding wires and metal bumps [3]. TSV is not new, but now it is finally an option [4].

TABLE I
COMPARISON BETWEEN ALTERNATIVE DESIGN
IMPLEMENTATIONS.

Property	Single chips	SOC	3D
Modular flexibility	High	Low	Medium
System performance	Low	Medium	High
Physical dimension	Large	Medium	Small
Complexity of fabrication	Low	Medium	Medium
Cost	Low	Medium	High
CAD tools and design methodologies	Available	Available	Not deployed yet

TABLE II
COMPARISON AMONG DIFFERENT 3D ASSEMBLY TECHNOLOGIES

Technologies	Advantages	Disadvantages
Wire bonding	-Flexible connection -high reliability -their processing is mature and cost effective	-Low density -Long wiring -Poor signal integrity -Large pad area
metal bumps	-Short length	-Large solder ball
TSVs	-Short length -High density -Small footprint	-Complex Fabrication
Contactless (inductive and capacitive coupling)	- reducing the length of electrical paths -simple fabrication	-less reliability -cross talk and coupling issues -size of inductors (inductive coupling)

Fig. 1 Reduction in wire length where the original 2-D circuit is implemented in two and four planes.

Fig. 2 A possible design for a 3D SoC (heterogeneous technologies).

Fig. 3 Examples of 3D structures with interconnection elements

The general structure of a TSV (Fig. 4) is typically a cylinder with a uniform circular cross-section of a conducting material (copper) surrounded by an insulator (silicon dioxide) which is intended to prevent leakage and resistive coupling through the substrate (silicon). 3D integrated circuits, which contain multiple layers of active devices, extensively utilize the vertical dimension to connect components. Usually, the TSV interconnections are fabricated as an array in a silicon substrate. TSVs distribution is mainly determined during physical design such as partitioning, placement, and routing. TSVs can be laid out in a row, within a regular matrix, or within an irregular distribution depending on the applications and technology constraints [1]-[4]. The characteristics of a TSV are dependent on its geometrical parameters (such as the TSV diameter, height, pitch, and oxide layer thickness) and

Fig. 4 The through silicon via structure assuming a uniform circular cross section of copper surrounded by an oxide inside a silicon substrate (a) 3D view (b) Top view (c) Side view.

electrical parameters (such as the metal conductivity, oxide permittivity, and the silicon substrate resistivity).

3D integration technology using TSVs is a relatively new research field. In this paper, we address technology trends for 3D integration, highlight the 3D/TSV modeling and design challenges, and review existing solutions. The rest of this paper is organized as follows. In Section II, the challenges of TSV-based 3D integration are discussed. Conclusions are given in Section III.

II. MODELING AND DESIGN CHALLENGES FOR 3D ICS

Although 3D ICs offer many advantages over 2D ICs, many challenges should be overcome before TSV-based 3D ICs production becomes possible. These challenges levels are shown in Fig. 5, and are discussed below:

Fig. 5 3D IC: the complete solution and challenges.

A. Electrical Modeling Challenges

The purpose of modeling interconnections is to extract equivalent circuits that describe the electrical characteristics of given interconnection structures. A major difficulty in modeling 3-D interconnections comes from the need to obtain the entire coupling model of a large number of 3D interconnections. Furthermore, for accurate electrical design of 3D ICs including radio frequency (RF), analog, and digital submodules, the 3-D interconnection model should cover a sufficiently wide frequency range. The broadband model needs to capture frequency-dependent losses, coupling, and mismatch, which are contributed by the parasitic elements such as series inductances, resistances, shunt capacitances, and conductance. Unlike conventional interconnects, a TSV is surrounded by the silicon substrate that has a finite resistivity. This finite resistivity results in a nonlinear capacitance and resistance parasitics that are not present in conventional interconnect, and a large capacitance that is highly dependent on TSV relative position to nearby body contact. Therefore, in case of modeling TSV interconnections, the silicon substrate should be considered as another source of loss. Clearly, TSV modeling is extremely challenging when a large number of TSV interconnections are involved. A typical lumped model of a single interconnection is composed of a series inductor, a series resistor, and a parallel capacitor. The values of circuit elements are determined by the shape of the interconnection itself as well as the coupling from nearby interconnections and other passive structures such as power/ground planes. The TSV is a more general structure than transmission lines. Thus, applying transmission line theory for 3-D interconnection modeling is not appropriate. Because of this fundamental difficulty with 3-D interconnection modeling, most previous research relied on indirect ways for characterization based on measurements, analytical methods, and numerical methods. The measurement-based equivalent model is difficult to extend to general multi-TSV structures due to the increased number of model parameters that need to be tuned to the multi-port measurement data. So the numerical methods are used[3].

One of the problems being researched in this domain is the modeling of multi-TSV arrangement in a 3-D system and their time-domain co-simulation in a simulator like SPICE. Most of previous work characterizes specific TSV structures but they do not address general multi-TSV problems [5]-[15]. Other related work proposes a model but no closed-form expressions are given for the TSV parasitic calculations [19]. In other words, there has been no related work in TSV macro-modeling. Also, few work addresses the multi-stacked TSV modeling problem.

B. Thermal Management Challenges

Thermal management is one of the important issues of 3D IC integration. So, effective thermal management methodologies and solutions are needed for widespread use of 3D IC integration. The thermal analysis is an important as from the thermal and stress distribution, we can make layout modification and thus enhance the circuit reliability. The

thermal issue of a 3D IC is much severer than that of a 2D IC. The cause is that the ambient environment of the die of a 2D IC is the cooling material, but the ambient environment of a die within a 3D IC may be another die that also generates heat. Therefore, Thermal management in 3D ICs is critical for maintaining required reliability, performance, and power dissipation target. Therefore, new cooling techniques must be innovated to ensure that the chip can operate at temperatures and performance required for reliability [20,21].

C. CAD Tools Challenges

The addition of a third dimension would require support from more advanced CAD tools (floorplan gets 3rd D). 3D IC physical design has attracted an increasing amount of attention. There is a significant amount of work on the floorplanning, placement and routing for 3D ICs. However, all these tools developed by different groups, using different formats to represent the design data, create barriers for researchers who need to make use of the existing design automation tools to conduct further studies on 3D IC. Also, there are a lack of CAD algorithms and only few commercially available EDA tools for 3D integrated circuits. Therefore, current 2D physical design tools (partitioning, placement, routing, timing, extraction, LVS, DRC) must enable 3D designs[22,23].

D. Technological, Yield and Test Challenges

There is new types of defects caused by TSV formation, and alignment (The alignment accuracy or bonding quality (including wafer to-wafer alignment)), a broad range of open issues are in a pressing need for novel ideas. Solutions are needed to address these challenges before 3D integration technology can be widely used [24]. Also, It is well known that yield has a quadratic dependency on die size, and a linear dependency on chip count at a given die size. 3D designs may incur some yield loss due to vertical vias, and may gain some yield due to density [25]. There is still a lack of pre-bond test, post-bond test and DFT solutions.

E. Design Methodologies and Circuit Architectures Challenges

3D design methodologies are still needed to reduce coupling between TSVs (body contacts reduces the current loop so it reduces the mutual inductances) and for clock and power distribution networks for 3D ICs. Also, more investigations are required for analyzing the effect of TSVs on signal integrity, power integrity and delay. The 3-D integration also provides opportunities for new circuit architectures. For example, a 2-D FPGA requires 2-D interconnections that grow faster than gate count. Thus, 2-D FPGAs are limited in performance by the complexities of their internal interconnections. A 3-D FPGA would overcome this

interconnect limitations, resulting in faster data throughput, and faster switching of the gate-level configuration.

Table III summarizes the 3D challenges and their related work status [26, 27].

TABLE III
3D CHALLENGES AND THEIR RELATED WORK STATUS

Challenge	Related Work Status
Electrical Modeling	Research initiated, some models are available
Thermal Modeling	Research initiated, some tools and techniques are available.
3D CAD Tools	No complete solution is available, research needed
Yield and Test	No solution is available, research is needed
Technological	Nearly Mature
Design Methodologies	No complete solution is available, research is needed

III. CONCLUSIONS

3D integration technology using TSV is one of possible future IC design technologies. It can offer many advantages over the existing 2D integration technology. However, many challenges (modeling, thermal, CAD tools, yield and test, technological, design methodologies, circuit architectures) should be overcome before TSV-based 3D ICs production becomes possible.

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