Ain-Sham University
Faculty of Engineering
Electronics and Communication Engineering Department

Design, Modeling, and Characterization of Three Dimensional Integrated Circuits

By

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A Dissertation

Submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Electrical Engineering, Communication and Electronics Branch

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CAIRO, EGYPT
2012

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Dedication

To the memory of my beloved father. To the martyrs of the Egyptian revolution.

Curriculum Vitae

Khaled S. Mohamed attended the school of Engineering, Department of Electronics and Communications at Ain-Shams University from 1998 to 2003, where he received his B.Sc. degree in Electronics and Communications Engineering with distinction and honors. He received his Masters degree in Electronics from Cairo University with distinction and honors on August 2008. Currently, he is working towards his PhD degree at Ain-Shams University, Cairo, Egypt. His research interests are in 3D integration modeling, characterization, and analysis.

Acknowledgements

First and foremost, I would like to express my sincere gratitude to my advisor Professor Yehea Ismail for his guidance and encouragement during the ragged path of the PhD program. His perspicacity, patience, persistence, intellectuality, and, in general, his thirst for perfection have immensely contributed to my evolution as a young researcher. I consider myself lucky to work for him and I honestly would not exchange my years as his advisee for any other Professor around this globe. Thank you Professor. I would also like to thank Professors Alaa El-Rouby, Hani Ragai, and Wagdy Anis for their help and guidance.

In addition, I would like to thank a few people who significantly helped me over these years. My previous manager at Mentor Graphics, Mohamed Salem, who allowed me to attend all my exams and lectures smoothly.

I express my deepest gratitude to my parents for their restless efforts on growing and taking care of me through thick and thin; I compliment most warmly my loving and caring wife, who had to endure and share the pain and the pleasures of my arduous professional life.

I greatly appreciate the financial support for my research from Mentor Graphics and the spiritual support from the managers.

Abstract

Design, Modeling, and Characterization of Three Dimensional Integrated Circuits

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This dissertation presents a wide-band SPICE-compatible *RLC* model for TSVs in 3D ICs. This model accounts for a variety of effects, including skin effect, depletion capacitance, and (more novel) nearby contact effects. The TSV is modeled like a MOS structure where it is assumed that a full depletion region exists around the TSV. A lumped parameter model is then proposed to model the TSV. The equivalent circuit model includes a single TSV model and coupling model between TSVs. For many structures, we determined *S*-parameters using field-solver and then the parameters are determined by fitting the S-parameters data with a TSV circuit model. Dimensional analysis is then applied to obtain closed form solutions for the resistance, capacitance, and inductance of the lumped model. The accuracy of the expressions is then verified with the electromagnetic field solver Ansoft Quick 3D (Q3D) under typical high-density TSV dimensions, and it shows a significant accuracy up to 100 GHz. The results also indicate that the MOS effect does not play a significant role in case of no body contacts. This is corroborated by the value obtained for C_{dep} and R_{dep} as compared to R_{si} and C_{si}. This shows that the MOS effect is very important in proximity of body contacts. Although, there are several models in the literature that provide an *RLC* model for a TSV and closed form expressions with different levels of accuracy, our models exhibit several additional enhancements as compared to existing literature: 1) MOS depletion *R* and *C* effect. 2) Body contact effect. 3) Model linearization, *i.e*, single nonlinear or frequency dependent element can be approximated by multiple linear, and frequency independent elements. 4) Simulation comparisons (e.g. with full-wave, quasi-static, and device simulation). This work

can be very useful in the fast parasitic extraction of TSVs for 3D IC design.

Moreover, a proposed architecture based on TSV technology for a spiral inductor is demonstrated and characterized. A closed form expression for the inductance is obtained and an analytical equation to calculate the maximum quality factor is derived. Simulation results indicate that our formulas are accurate.

Also, in this research, and for the first time, a novel inductive coupling interface that uses the magnetic near field induced by TSV-based spiral inductor is demonstrated. The feasibility of using TSV for wireless near field communication is shown. A TSV-based near-field inductive-coupling system offers a high quality factor and a good coupling coefficient. Therefore, the proposed communication system appears to be a promising technology for wireless communication. To our knowledge, this is the first work on this topic.

Key Words: Three-Dimensional ICs, Through Silicon Via, Modeling, TSV, Dimensional Analysis, Macro- Modeling, Spiral Inductor, Quality factor (Q), Self-Resonance Frequency, and Wireless.

Summary

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This dissertation consists of the following chapters:

Chapter One introduces ongoing trends to work around Moore's law limitations. Moreover, this chapter focuses on technology level trends, where it presents new architectures, materials, interconnect schemes, and devices. Technology trends for 3D integration, highlights of the 3D/TSV modeling and design challenges, and review of existing solutions are included. Motivation, previous work, and contributions are also presented in this chapter.

Chapter Two proposes a TSV modeling methodology. Moreover, the TSV is physically modeled and characterized, different multi-TSVs structures are investigated and the proposed lumped element model for multi-TSV arrangements and closed form formulas are introduced. Also, the TSV model linearization is introduced and the proposed models for multi-TSV arrangements are validated versus electromagnetic simulations in the frequency and time domains. The TSV impact on circuit performance is also investigated.

Chapter Three presents a TSV-Based On-Chip Spiral Inductor. A closed form expression for the inductance is obtained and analytical equation to calculate the maximum quality factor is derived.

Chapter Four presents a novel TSV-Based On-Chip Wireless Communications. The feasibility of using TSV for wireless near field communication is analyzed and verified.

Chapter Five concludes this dissertation and proposes future work.

List of Publications

1. **Khaled Salah**, Alaa El-Rouby, Yehea Ismail, and Hani Ragai "TSV-Based On-Chip Spiral Inductor and Near-Field Wireless Communications" DAC, WIP, 2012.
2. **Khaled Salah**, Alaa El-Rouby, Yehea Ismail, and Hani Ragai "A Closed Form Expression for TSV-Based On- Chip Spiral Inductor" ISCAS, 2012.
3. **Khaled Salah,** Alaa El-Rouby, Yehea Ismail, and Hani Ragai "A Novel Inductive Coupling Communications Based on Through Silicon Via Technology" DATE, Workshop on 3D, 2012.
4. **Khaled Salah**, Alaa El-Rouby, Yehea Ismail, and Hani Ragai "Compact Lumped Element Model for TSV in 3D-ICs" ISCAS, 2011.
5. **Khaled Salah**, Alaa El-Rouby, Yehea Ismail, and Hani Ragai "Lumped Element Models for Various n-Ports through Silicon Vias Networks" ASP-DAC, 2011.
6. **Khaled Salah**, Alaa El-Rouby, Yehea Ismail, and Hani Ragai "TSV Model Linearization" ICM, 2011.
7. **Khaled Salah**, Alaa El-Rouby, Yehea Ismail, and Hani Ragai "TSVs Macro-Modeling Framework" ICEAC, 2011.
8. **Khaled Salah**, Alaa El-Rouby, Yehea Ismail, and Hani Ragai "Body Contact Based TSV Equalizer" IDT/ICECS, 2011.
9. **Khaled Salah,** Alaa El-Rouby, Yehea Ismail, and Hani Ragai "A Comprehensive SPICE Compatible Through Silicon Via Model" VM-FEDA, 2011.
10. **Khaled Salah**, Alaa El-Rouby, Yehea Ismail, and Hani Ragai "Compact TSV Modeling for Low Power Application" ICEAC, 2010.
11. **Khaled Salah**, Alaa El-Rouby, Yehea Ismail, and Hani Ragai "TSV Enabling Technologies for SoC/NoC: Modeling and Design Challenges" ICM, 2010.

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