Elektrotechnik

David Dahl

Electromagnetic Modeling and Optimization of Through Silicon Vias

SHAKER
VERLAG

Electromagnetic Modeling and Optimization of Through Silicon Vias

Vom Promotionsausschuss der
Technischen Universität Hamburg-Harburg
zur Erlangung des akademischen Grades
Doktor-Ingenieur (Dr.-Ing.)
genehmigte Dissertation

von
David Dahl

aus
Mölln

2017

1. Gutachter:
Prof. Dr. sc. techn. Christian Schuster

2. Gutachter:
Prof. Dr. Klaus-Dieter Lang

3. Gutachter:
Dr.-Ing. Ivan Ndip

Vorsitzender des Prüfungsausschusses:
Prof. Dr.-Ing. Gerhard Bauch

Tag der mündlichen Prüfung:
13.12.2017

Berichte aus der Elektrotechnik

David Dahl

Electromagnetic Modeling and Optimization of Through Silicon Vias

Shaker Verlag
Aachen 2018

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at http://dnb.d-nb.de.

Zugl.: Hamburg-Harburg, Techn. Univ., Diss., 2017

Printed in Germany.

ISBN 978-3-8440-6009-6
ISSN 0945-0718

Shaker Verlag GmbH • P.O. BOX 101818 • D-52018 Aachen
Phone: 0049/2407/9596-0 • Telefax: 0049/2407/9596-9
Internet: www.shaker.de • e-mail: info@shaker.de

Summary

This thesis presents work in the area of electromagnetic modeling of through silicon vias (TSVs). TSVs are vertical interconnects in silicon wafers and an important component for the three-dimensional integration that is required for the further increase in performance of integrated circuits and integrated systems.

Major parts of this thesis discuss the adaptation of the physics-based modeling approach from the original application for the modeling of vias in printed circuit boards to the application in interposers with a sufficient amount of metallizations of the substrate. Adaptations are necessary because the substrate can show significant conductivity and has to be regarded as a layered medium. The latter is due to the required dielectric insulators and due to oxide layers that results from the TSV fabrication process. Further layers need to be included in the analysis if the depletion layer effects due to the metal-oxide-insulator interface are to be considered.

The adaptations consist in the adaptation of a far field model for which an effective wave number of radial wave propagation in the layered medium is computed. They consist also in the computation of a near field model for the mode conversion at the junction between coaxial ports at the top and bottom of the interposer and the inner radial ports that connect to the far field model. In conjunction, the adaptations lead to an efficient and exact modeling over a large parameter range.

The efficient modeling is further applied to large scale crosstalk analysis. A measure for the effective total crosstalk of uncorrelated signal alongs the channels for single-ended links is defined and analyzed for several parameter variations. This measure allows for the investigation of the influence of several important design parameters of silicon interposers on the crosstalk.

Several test structures with TSVs have been fabricated and measured. Using full-wave simulations, the measurement results have been validated.

Acknowledgment

This thesis presents the results of my work carried out as a research assistant at the Institute of Electromagnetic Theory at Hamburg University of Technology in the time from October 2012 to April 2017. Most of the work was part of the project "Electrical Modeling and Design of Through Silicon Vias for Integrated Systems". This project, funded by the DFG (Deutsche Forschungsgemeinschaft), was a collaboration between the Institute of Electromagnetic Theory, the Fraunhofer Institute of Reliability and Microintegration (IZM) located in Berlin, and the Technical University Berlin (TUB).

First of all, I am very grateful to my doctoral adviser Prof. Dr. sc. techn. Christian Schuster for giving me the opportunity to work on this interesting topic. His continuous guidance and advice, honest feedback, dedication, and the inspiration for research greatly inspired this work.

I would like to thank Prof. Dr. Klaus-Dieter Lang and Dr.-Ing. Ivan Ndip for serving as second and third examiner of this thesis and for the fruitful cooperation throughout the project. The feedback during regular teleconferences and the organization of the test wafer fabrication are highly appreciated. I would also like to thank Anne Beyreuther for the work at IZM during the first part of the project, especially the organization related to the test structure design and fabrication.

I am grateful for the pleasant and motivating working atmosphere at the institute. Special thanks go to Dr.-Ing. Xiaomin Duan for mentoring the beginning of my research by introducing me to several subjects of modeling and simulation and for the continued collaboration as a member of IZM later in the project. I would like to thank Dr.-Ing. Miroslav Kotzev for introducing me to high-frequency measurement techniques and the advice on many practical aspects. I want to express my gratitude to my former fellow student and colleague Dr.-Ing. Alexander Vogt for encouraging me to apply for the PhD position. I would like to thank my former colleagues Dr.-Ing. Andreas Hardock and Dr.-Ing. Sebastian Müller for fruitful discussions and support. I am thankful to Katharina Scharff, Dr.-Ing. Heinz-Dietrich Brüns, Dr.-Ing. Jan Preibisch, Torsten Reuschel, and Ömer Yildiz for numerous helpful discussions and proof-reading parts of my thesis. The administrative and technical support of Heike Herder, Angela Freiberg, Stefan Conradi, and Volker Paulsen is highly appreciated.

Finally, I want to thank my parents, Eva and Peter, and my brother Jonas for their support and encouragement. I am indebted to Katharina for great motivation and support, especially during the final months of work for this thesis. Thank you!

Contents

Notation, Symbols and Acronyms

Notation

a	Scalar
$\boldsymbol{r}$	Vector
$\hat{\boldsymbol{r}}$	Unit vector in direction of $\boldsymbol{r}$
$\boldsymbol{e}_{\xi}$	Unit vector along coordinate ξ
$\boldsymbol{M}$	Matrix

Symbols

$\mathbf{1}$	Identity matrix
α	Attenuation constant (Np/m)
β	Phase constant (rad/m)
C	Capacitance (F)
E	Electric field strength ($\mathrm{V\,m^{-1}}$)
ε	Permittivity
$\underline{\varepsilon}$	Complex permittivity ($\underline{\varepsilon} = \varepsilon_r\varepsilon_0 - j\sigma/\omega$)
ε_r	Relative permittivity
ε_0	Permittivity of free space ($\varepsilon_0 \approx 8.854\,188 \times 10^{-12}\,\mathrm{F\,m^{-1}}$)
η	Wave impedance (Ω)
G	Conductance (S)
γ	Propagation constant ($\mathrm{m^{-1}}$)
H	Magnetic field strength ($\mathrm{A\,m^{-1}}$)
$H_n^{(1)}(\cdot)$	Hankel function of the first kind and order n
$H_n^{(2)}(\cdot)$	Hankel function of the second kind and order n
I	Electric current (A)
$\Im$	Imaginary part
j	Imaginary unit
$\mathbf{J}$	Matrix of ones
k	Complex wave number ($\mathrm{m^{-1}}$)

L	Inductance (H)
μ_r	Relative permeability of a medium
μ_0	Permeability of free space ($\mu_0 = 4\pi \times 10^{-7}\,\mathrm{H\,m^{-1}}$)
∇	Nabla operator
ω	Angular frequency ($\mathrm{rad\,s^{-1}}$)
R	Resistance (Ω)
$\Re$	Real part
$\mathrm{S}_{n,o}$	Scattering parameter from port o to port n (normalized to $50\,\Omega$ if not stated otherwise)
σ	Electrical conductivity (S/m)
σ_{SD}	Standard deviation
$\tan\delta$	Dielectric loss tangent
V	Electric voltage (V)
Y	Admittance (S)
$Y_{n,o}$	Admittance parameter from port o to port n
Z	Impedance (Ω)
$Z_{n,o}$	Impedance parameter from port o to port n
$\mathbb{Z}$	Set of all integer numbers

Acronyms

2D	two–dimensional
3D	three–dimensional
AC	alternating current
APM	argument principle method
BCB	benzocyclobutene
BOR	body of revolution
CIM	contour integral method
CPU	central processing unit
CTE	coefficient of thermal expansion
CVD	chemical vapor deposition
DUT	device under test
FDFD	finite difference frequency domain
FEM	finite element method
FEXT	far–end cross talk

FFT	fast Fourier transform
FWHM	full width at half maximum
GND	ground
GPIB	General Purpose Interface Bus
GSG	ground–signal–ground
IC	integrated circuit
ISI	inter symbol interference
ITRS	International Technology Roadmap for Semiconductors [1]
LRM	line–reflect–match (calibration)
MEM	multipole expansion
MEMS	micro–electro–mechanical systems
MOS	metal–oxide–semiconductor
MTL	multi–conductor transmission lines
MtM	more–than–Moore
NEXT	near end cross talk
PC	personal computer
PCB	printed circuit board
PDF	probability density function
PEC	perfect electrically conducting
PI	power integrity
PMC	perfect magnetically conducting
PMF	probability mass function
PRBS	pseudo random bit sequence
PSXT	power of cross talk
PUL	per–unit–length
RAM	random–access memory
RDL	redistribution layer
SACVD	sub-atmospheric chemical vapor deposition
SI	signal integrity
Si	silicon
SiO_2	silicon dioxide
SiP	system in package
SIW	substrate integrated waveguide
SoP	system on package
TEM	transverse electromagnetic
TM	transverse magnetic
TRM	transverse resonance method
TSV	through silicon via

TWA	thin wire approximation (→ Section 7.1.4)
UI	unit interval
USB	universal serial bus
via	vertical interconnect access
VNA	vector network analyzer
WPR	wafer photo resist (used as trade name, cf. Fig. 7.9)
WPSXT	weighted power sum of crosstalk
XTALK	crosstalk