国外电子信息精品著作（影印版）

芯片和系统的电源完整性建模与设计

Power Integrity Modeling and Design for Semiconductors and Systems

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内 容 简 介

本书包括电源完整性设计和建模两部分内容,重点在建模方面。全书分五章,涵盖了从基础知识到高级应用所需了解的各个细节。书中通过真实的案例分析和可下载的软件实例,描述了当今高效电源分配和噪声最小化的设计与建模的前沿技术,其中很多例子可以进行再仿真实现,这些可以用来评估常用的商用软件的准确性和速度。

本书适合研究电源完整性的学生、学者及工程师使用。

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《国外电子信息精品著作》序

20 世纪 90 年代以来，信息科学技术成为世界经济的中坚力量。随着经济全球化的进一步发展，以微电子、计算机、通信和网络技术为代表的信息技术，成为人类社会进步过程中发展最快、渗透性最强、应用面最广的关键技术。信息技术的发展带动了微电子、计算机、通信、网络、超导等产业的发展，促进了生命科学、新材料、能源、航空航天等高新技术产业的成长。信息产业的发展水平不仅是社会物质生产、文化进步的基本要素和必备条件，也是衡量一个国家的综合国力、国际竞争力和发展水平的重要标志。在中国，信息产业在国民经济发展中占有举足轻重的地位，成为国民经济重要支柱产业。然而，中国的信息科学支持技术发展的力度不够，信息技术还处于比较落后的水平，因此，快速发展信息科学技术成为我国迫在眉睫的大事。

要使我国的信息技术更好地发展起来，需要科学工作者和工程技术人员付出艰辛的努力。此外，我们要从客观上为科学工作者和工程技术人员创造更有利于发展的环境，加强对信息技术的支持与投资力度，其中也包括与信息技术相关的图书出版工作。

从出版的角度考虑，除了较好较快地出版具有自主知识产权的成果外，引进国外的优秀出版物是大有裨益的。洋为中用，将国外的优秀著作引进到国内，促进最新的科技成就迅速转化为我们自己的智力成果，无疑是值得高度重视的。科学出版社引进一批国外知名出版社的优秀著作，使我国从事信息技术的广大科学工作者和工程技术人员能以较低的价格购买，对于推动我国信息技术领域的科研与教学是十分有益的事。

此次科学出版社在广泛征求专家意见的基础上，经过反复论证、仔细遴选，共引进了接近 30 本外版书，大体上可以分为两类，第一类是基础理论著作，第二类是工程应用方面的著作。所有的著作都涉及信息领域的最新成果，大多数是 2005 年后出版的，力求“层次高、

内容新、参考性强”。在内容和形式上都体现了科学出版社一贯奉行的严谨作风。

当然，这批书只能涵盖信息科学技术的一部分，所以这项工作还应该继续下去。对于一些读者面较广、观点新颖、国内缺乏的好书还应该翻译成中文出版，这有利于知识更好更快地传播。同时，我也希望广大读者提出好的建议，以改进和完善丛书的出版工作。

总之，我对科学出版社引进外版书这一举措表示热烈的支持，并盼望这一工作取得更大的成绩。

王越

中国科学院院士

中国工程院院士

2006年12月

This book is dedicated to my father, K. Swaminathan, who taught me perseverance, and to my mother, Rajam Swaminathan, who taught me patience, two qualities I have learned to cherish.

—Madhavan Swaminathan

To my mother and father, Tanju and Burhan Engin.

—A. Ege Engin

PREFACE

During my (M.S.) undergraduate days in a little town called Tiruchirapalli in Southern India, we used to have frequent voltage and current surges that knocked out all the electrical equipment such as fans and lights in our rooms. Frustrated, my friend once remarked, "We are *powerless* to solve the *current* problem." Of course, he meant this in jest, but little did I realize that his statement would become the theme of my research for many years. Although my area of specialty is semiconductors and computer systems, the issues related to power haven't changed.

Power represents the major bottleneck in modern semiconductors and systems. With transistor scaling over the last two decades, Moore's law has enabled the integration of millions of transistors within an integrated circuit. With lower gate capacitance and lower voltage, faster transistors have become available with each new generation of computers. However, increased transistor integration has resulted in an increase in the current supplied to the integrated circuit, thereby increasing power. Managing the *transient current* supplied to the integrated circuit at gigahertz frequencies is one of the biggest challenges faced by the semiconductor industry. With lowering of the supply voltage to the transistors, dynamic variation in the power supply due to current transients is becoming a major bottleneck. The dynamic variation of the supply voltage, also called power supply noise, delta I noise, or simultaneous switching noise, is the subject of this book.

Managing power integrity is the process by which the variations on the power supply of the transistors can be maintained within a specified tolerance value. Noise on the power supply can have a direct influence on the speed of an integrated circuit, and hence supplying clean power is a very important element in the design of a computer system. A power distribution network consists of interconnections in the chip, package, and board that include decoupling capacitors, ferrite beads, DC–DC converters, and other components. Both the package and board form a very critical part of the power distribution network, which is the focus of this book.

The book covers two aspects of power distribution: design and modeling, with an emphasis on modeling. The book is organized into five chapters, which cover basic and advanced concepts. All chapters contain several examples to illustrate the concepts, some of which can be reproduced using the software provided. These examples can also be used to evaluate the accuracy and speed of several commercial tools that are available today.

Chapter 1, "Basic Concepts," is for engineers and students who are entering the field of power integrity. The basic concepts are covered in this chapter, which includes a discussion on the fundamentals of power supply noise, its role in the speed of a computer system, the parasitics that produce it, and its effect on jitter and voltage margin for high-speed signal propagation. A power distribution network is best designed in the frequency domain, and the reasons for this are discussed in this chapter. The entire book is based on the parameter called *target impedance*, which can be used to evaluate the properties of a power distribution network. This parameter, developed in the mid-1990s, provides an elegant method of analysis, which can be used to understand the role of various components in the response of a power distribution network. The target impedance is therefore explained in detail in Chapter 1, with examples that can be reproduced using a circuit simulator such as Simulated Program with Integrated Circuit Emphasis (Spice). The concept of target impedance is used to promote better understanding of the placement of decoupling capacitors. The components of a power distribution network consist of several voltage regulator modules, decoupling capacitors, package and board interconnections, planes, and on-chip interconnections, each of which are explained in this chapter. Planes represent a very critical part of modern power distribution networks. Their frequency behavior can either reduce power supply noise or increase it by a large amount. Hence, a fundamental understanding of plane behavior and its effect on advanced power distribution networks is necessary. The entire book is centered around planes from both a modeling and design standpoint. The fundamental behavior of planes is covered in Chapter 1, with a focus on standing waves, their frequency of occurrence, capacitive and inductive behavior, and use of decoupling capacitors to minimize their effect. The interaction between components of a power distribution is as important as the components themselves. For example, a surface-mount device (SMD) capacitor can interact with the via inductance, causing the self-resonance frequency to shift to a lower frequency; the chip can interact with the package, causing an antiresonance; or the power supply noise can couple into a signal line, causing excessive jitter. The basics associated with such phenomena are covered in Chapter 1. Finally, a methodology is presented that centers on frequency domain analysis initially followed by time domain analysis. The authors believe that this is the optimum way for analyzing and designing advanced power distribution networks.

A power distribution network containing suitably designed planes, signals well referenced to planes, and decoupling capacitors appropriately placed on planes will always result in minimum power supply noise. Planes are therefore the focus of Chapter 2, "Modeling of Planes," which covers the various methods available for plane modeling. Some of these methods are used by commercial tools today. This chapter, which requires some background in numerical modeling, provides a survey of modeling methods along with examples that are useful to a designer and can be used to evaluate commercial tools for accuracy and speed. The in-depth numerical formulations can be reproduced in MATLAB and hence are useful to both students and application engineers who are interested in power integrity modeling. Since Maxwell's equations have been converted into circuit representations, we believe that the numerical formulations in this chapter are easier to understand. The modeling methods are separated into lumped element modeling and distributed modeling methods, each covered in detail. The chapter starts with modeling a plane pair and then explains modeling of multilayered planes. The coupling effects in multilayered planes, which include field penetration concepts, aperture coupling, and wraparound currents, are discussed, and the plane modeling methods are compared from a qualitative standpoint. This comparison, along with the rest of the chapter, allows an engineer to benchmark commercial tools.

Signals from the output of a driver are propagated on signal line interconnections. However, the driver requires voltage and current to function, and these are supplied by the power distribution network. The signal and power interconnections therefore have to be coupled, with noise on one producing noise on the other. Hence, managing both signal and power integrity requires an understanding of the coupling mechanism between the signal lines and planes. Chapter 3, "Simultaneous Switching Noise," requires little understanding of numerical methods. The entire chapter is based on circuit-level implementations using a concept called *modal decomposition*, which allows the separation of signal lines from the power distribution network so that each can be analyzed separately and later combined for analysis. Simple Spice models can be used to capture modal decomposition using coupling coefficients and controlled current or voltage sources. The important concept to understand in this chapter is the role of return currents—a concept that every power integrity engineer must understand for minimizing noise.

Chapter 4, "Time-Domain Simulation Methods," describes methods for converting a frequency response into a Spice subcircuit. Also called *macromodeling,* this is a new area of time-domain simulation that is ripe for research. We include this chapter in the book because a few commercial electronic design automation (EDA) vendors have started developing tools in this area. The purpose of Chapter 4 is to enable an engineer or student to better understand the issues involved. The early part of the chapter is easy to follow; it requires some mathematics background and is therefore targeted at designers who use commercial tools. Several examples illustrate simple concepts that can be reproduced using MATLAB. The latter part of the chapter is intense and is mainly intended for people working in the numerical modeling area. The purpose of this chapter is to provide an introduction to the issues involved and possible solutions.

In Chapter 5, "Applications," all of the issues discussed in Chapters 1 to 4 are linked to real-world examples. Several examples from companies such as Sun Microsystems, IBM, Oak Mitsui, National Semiconductor, Cisco, DuPont, Panasonic, and Rambus are provided. These applications cover both design and modeling aspects of power integrity. Each example was chosen carefully to ensure that a specific aspect of power integrity is addressed.

The best part of the book is that it reproduces some of the examples using the software provided. We hope that through this software, some of the subtle effects related to power integrity, which are only discussed in research papers, can be reproduced and appreciated by a larger community.

Madhavan Swaminathan (M. S.)
A. Ege Engin (A. E. E.)

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The power integrity work discussed in this book started in the mid-1990s when I had the opportunity to collaborate with Larry Smith and Istvan Novak of Sun Microsystems. This collaboration over a 5-year period laid the foundation for the work described in this book. I am forever grateful to both Larry and Istvan for providing me insights into the power distribution issues, making available several test vehicles, and providing access to system-level measurements. Both Larry and Istvan are my good friends, and I continue to consult with them.

Around 2000, I started working with James Libous of IBM through an SRC project. Work over the next several years resulted in some very interesting ideas in power integrity modeling. In research, not every idea results in a useful solution. However, without trying out new ideas, advancements are not possible. I am forever indebted to Jim for providing me unconditional support for my research without raising any doubts whatsoever on the validity of the solutions. Through his mentorship and leadership of the SRC project, I had a number of students work on very interesting problems related to power integrity, most of which have been captured in this book.

My move to Georgia Tech in 1994 is what started all of my research on power integrity. I was recruited by Professor Rao Tummala, a former IBM Fellow who is currently a chaired professor at Georgia Tech, and Professor Roger Webb, the former Chair of Electrical and Computer Engineering at Georgia Tech. Through their mentorship and guidance, I was able to start a research program and I am forever thankful to them.

My strength has always been my students. I have challenged them in research and have often made unreasonable demands, but my students have always delivered. This book is a result of their hard work over a 10-year period. I would like to acknowledge the support of all my students and in particular the following graduate students who made a direct contribution to this book: Nanju Na, Jinseong Choi, Sungjun Chun, Joongho Kim, Sunghwan Min, Rohan Mandrekar, Jifeng Mao, Jinwoo Choi, Vinu Govind, Krishna Bharath, Abdemanaf Tamabawala, Krishna Srinivasan, Lalgudi Subramaniam, Prathap Muthana, Tae Hong Kim, Ki Jin Han, Janani Chandrasekhar, and Bernard Yang. Some of them have graduated, but I continue to interact with them.

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I have wanted to write a book on power integrity for several years. It all became possible after my coauthor, Ege Engin, joined my research program in 2005. Through his hard work and meticulous planning, we were able to complete this book. My thanks go to him.

A very important element of this book is the software. User-friendly software is always very difficult to develop. I would like to thank Andy Seo, who spent several nights developing the graphical user interface for the Sphinx software program, described in Appendix B. I am also very thankful to Sunghwan Min, who developed BEMP, described in Chapter 4 and Appendix B.

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Madhavan Swaminathan

Let me begin by expressing my thanks to the many reviewers of this book, whose names are given above. I started working on power integrity during my Ph.D., while I was working as a research engineer at the Fraunhofer Institute for Reliability and Microintegration in Berlin, Germany. Among my many former colleagues, I would especially like to thank Uwe Keller and Umberto Paoletti for the inspiring discussions on computational electromagnetics, and Ivan Ndip for the discussions on high-speed design. My Ph.D. advisor, Professor Wolfgang Mathis of the University of Hannover, has shown me new ways of looking at power-integrity modeling from a circuit point of view. I would like to thank him and my coadvisor, Professor Herbert Reichl of the Fraunhofer Institute, both of whom have always supported me.

After I completed my Ph.D., I moved to Georgia Tech to work with Professor Madhavan Swaminathan, who encouraged me to coauthor this book. It is a pleasure for me to acknowledge his mentorship and to thank him for it. I would also like to thank Professor Rao Tummala from the Packaging Research Center at Georgia Tech for his continuous support.

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A. Ege Engin

ABOUT THE AUTHORS

Madhavan Swaminathan received his B.E. in electronics and communication from Regional Engineering College, Tiruchirapalli, in 1985, and his M.S. and Ph.D. in electrical engineering from Syracuse University in 1989 and 1991. He is currently the Joseph M. Pettit Professor in Electronics in the School of Electrical and Computer Engineering and deputy director of the Packaging Research Center, Georgia Tech. He is also the cofounder of Jacket Micro Devices, a company specializing in RF modules for wireless applications. Before joining Georgia Tech, he worked on packaging for supercomputers for IBM. Swaminathan has written more than 300 publications, holds 15 patents, and has been honored as an IEEE Fellow for his work on power delivery.

A. Ege Engin received his B.S. and M.S. in electrical engineering from Middle East Technical University, Ankara, Turkey, and from the University of Paderborn, Germany. From 2001 to 2004, he was with the Fraunhofer Institute for Reliability and Microintegration in Berlin. During this time, he also received his Ph.D. from the University of Hannover, Germany. He is currently a research engineer in the School of Electrical and Computer Engineering and an assistant research director of the Packaging Research Center at Georgia Tech. He has more than 50 publications in refereed journals and conferences in the areas of signal and power integrity modeling and simulation.

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