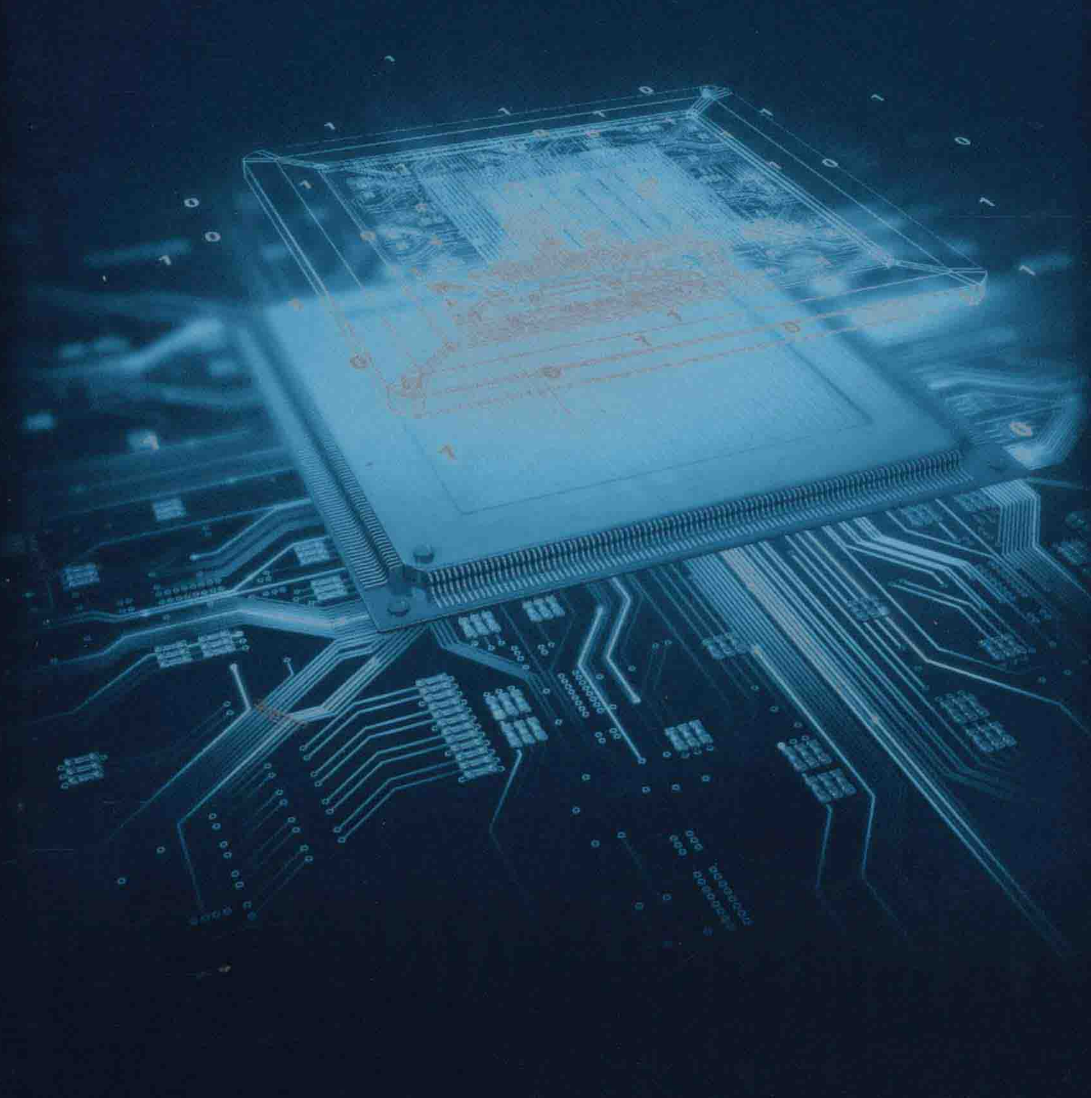
Microwave and RF Semiconductor Control Device Modeling

Robert H. Caverly



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ARTECH HOUSE

BOSTON | LONDON
artechhouse.com

Library of Congress Cataloging-in-Publication Data
A catalog record for this book is available from the U.S. Library of Congress

British Library Cataloguing in Publication Data
A catalog record for this book is available from the British Library.

ISBN-13: 978-1-63081-021-4

Cover design by John Gomes

685 Canton Street
Norwood, MA

10 9 8 7 6 5 4 3 2 1

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To my wife,
Maggie

Preface

The microwave and RF design engineer always seeks to develop a design that will meet specifications the first time that the circuit is fabricated. To do so requires that as many elements and phenomena as possible associated with the control devices and circuit be accurately modeled. In the case of the microwave and RF semiconductor control circuits, accurate modeling of the solid-state control components over frequency, voltage, current, and power is key to successful control system design. This book was written to provide the RF and microwave design engineer insight into the physical operation and modeling of PIN diodes and field-effect transistors (FETs) as control components and their use in microwave and RF control circuits. This insight I hope will be of some aid to design engineers to help them wisely choose and adapt device and circuit parameters during design optimization for best circuit performance.

The book is organized in the following manner. Chapters 1 and 2 cover fundamental material that provide the foundation for better understanding of the control device models introduced in later chapters. These two chapters cover the basics of control circuits, noise theory, device packaging issues, thermal behavior, and nonlinear device theory. Forward and reverse bias operation of the PIN diode in both switch states is the subject of Chapters 3 and 4. Chapter 3 focuses on the theory of operation of the PIN diode as an RF and microwave control element. The linear modeling of this operation is extensively covered. Chapter 4 expands on this modeling of the linear operation of the PIN diode and presents modeling of the device's nonlinear behavior and the subsequent introduction of unwanted signals into the circuit. Chapters 5 and 6 present the theory, operation, and modeling of FET-based control devices, with the metal-oxide-semiconductor FET (MOSFET) and metal-semiconductor FET (MESFET) being the two main focus technologies. Because the operation of the MOSFET and MESFET is fundamentally different, the operation and modeling of each device is covered in separate chapters. Chapter 5 covers the linear and nonlinear on- and off-state operation of the silicon MOSFET, focusing on the n-channel device. Chapter 6 covers the linear and nonlinear operation of the MESFET: traditional MESFETs and high electron mobility MESFET (HEMTs) in both operational states is discussed. The final two chapters, Chapters 7 and 8, present example control circuit simulations based on the PIN diode and FET models presented in the earlier chapters and provide a basis for further exploration of control device operation. The author, with the gracious agreement of Artech House, has placed simulation files and other support resources and files described in more detail in Chapter 1 on the web at a SourceForge repository: http://sourceforge.net/projects/pindiodemodel/files/

Acknowledgments

I have spent most of my engineering career working on microwave and RF control devices, and there have been many people I have collaborated with and discussed details of the operation of these components. If you are not mentioned in these acknowledgments, please be assured that I appreciate all the insights that I gained through our discussions.

I would first like to thank Wesley Fields and Rockford Curby at Cobham Metilics for their help in obtaining the photographs of various PIN diode packages and micrographs in Chapters 2 and 3. They explained in one picture what would have taken me many words to present. My Artech House editors, Marissa Koors and Molly Klemarczyk, provided invaluable assistance in keeping the book on track, keeping me aware of upcoming deadlines, and generally guiding me through all aspects of the development and production process. I also wish to thank Mark Walsh of Artech House for his assistance during the preliminary stages of the book development in helping me with understanding the entire publishing process and for being supportive of this endeavor over the many years prior to the book actually being written. Dr. Steve Maas was also extremely helpful in the proposal stages of the book, providing valuable suggestions that helped strengthen the presentation of the material. In addition to the editors, the technical reviewer gave me many suggestions in improving the overall manuscript; I used practically all of them.

In my first book, I acknowledged two individuals that gave me general but invaluable advice in the mechanics of book writing, advising me to stick to a strict and detailed outline and to schedule and keep plugging away on a daily basis: Dr. Steve Maas and Dr. William Bushong. Their advice stood the test of time and was still valuable in the writing of this book. I collaborated with Gerald (Jerry) Hiller for almost 20 years on modeling of microwave and RF control devices, and I am honored to have had the opportunity to work with him. I also wish to thank William E. Doherty, Jr. and Ronald Watkins for a collaboration that spanned almost 10 years and who first introduced me to the MRI field. Other acknowledgments go to Dr. Peter Rizzi, who was a mentor early in my career, and to the Amateur Radio community at large for using microwaves and RF as a hobby.

Putting together a book like this takes many hours of work a day. I thank my family for putting up with the long hours spent at my computer during the book's preparation. I'd like to thank my two sons, William and Matthew, for their interest in the progress of the book. Finally, I want to thank my wife, Maggie, for her patience and support during the writing of the book.

Robert H. Caverly, PhD
January 2016

Contents

CHAPTER 1

Introduction

1.1 Historical Perspective and Background

The modern era of semiconductor radio frequency (RF) and microwave control began more than a half-century ago, soon after the invention of the transistor. For the previous 50 years, semiconductor devices were used at RF and microwave frequencies, using such fragile devices as "cat whiskers," and point contact diode technologies [1–5]. With the advent of more reliable commercial semiconductor diodes in the 1950s, theoretical and applied research for RF and microwave control applications increased dramatically. At the time, both germanium and silicon diodes were available, with the most famous being the n-type germanium 1N263 and the p-type silicon 1N23B [6]. Interestingly, the 1N263 exhibited superior performance when used as a waveguide switch compared with the 1N23B [7]. This superior performance was attributed to the difference in the hole and electron mobilities between the two semiconductor and doping types [6, 7]. Garver published a series of papers in the 1950s and 1960s that described the theory and operation of these waveguide switching diodes in great detail and provided a solid foundation for further work on the subject [7–9]. Uhlir described the concept of using a PIN diode, a relatively new type of diode structure at the time, as a variable resistor at RF and microwave frequencies in 1958 [10, 11]. The PIN diode was first introduced as a high-voltage rectifier but was found to be a poor rectifier above a few megahertz [11]. Further investigation, however, showed the diode to have controllable impedance at very high frequencies [11]. This opened up the possibility of accurate control of RF and microwave signals with variable dc forward bias; this ability to vary the amplitude gave rise to the term variolosser [12]. White wrote the first and what is still considered to be one of the standard microwave semiconductor control texts on applications of PIN diodes [13]. Research on microwave and RF control devices continued during this time on not just discrete PIN diodes. One of the first silicon monolithic microwave integrated circuits (MMIC) was a PIN diode transmit-receive switch [14]. Since that time, control circuit designs using PIN diodes in both discrete and monolithic form for RF and microwave control applications have expanded from these early radar applications to wide-ranging applications in personal and infrastructure communication systems and even medical applications, such as in magnetic resonance imaging (MRI) scanners.

From the 1950s onward, transistors were being intensely investigated for many uses, including RF and microwave control. The first usable microwave bipolar transistor was introduced in 1965, and steady progress in frequency and performance has continued to this day. The use of field effect transistors (FETs) for microwave applications started in 1971; Liechti published an excellent review of the development history of FETs up to 1976 [15]. Garver, who published extensively in the 1950s and 1960s on RF and microwave diode control, in 1979 discussed using FETs instead of diodes for RF and microwave control [9]. The next year, Ayasli and colleagues developed a gallium arsenide-based (GaAs) monolithic FET transmit-receive switch, followed up two years later by a switch with higher power handling [16, 17]. The first RF and microwave control FETs were of the metal-semiconductor (MESFET) type, but as digital complementary metal-oxide-semiconductor (CMOS) FETs improved in performance due to decreasing feature size, MOSFETs started to play a larger role in the control area. Since the MESFET and MOSFET are easy to include with other digital and analog circuitry on an integrated circuit, their use has important impact on fully monolithic integrated communication and other system-on-chip (SoC) solutions.

Increase in circuit and system complexity requires the designer to use computer tools to reduce design time and increase the probability of first-pass design success. Computer design tools are only as good as the models they use, and modeling of semiconductor control devices is no exception. This book seeks to provide the theoretical background governing the operation of these semiconductor control devices and to link this theoretical understanding to the computer models that aid in simulating the device's behavior at the circuit level. It is hoped that the reader will gain better insight into the physical operation of these devices during the design process and understand the interplay between device model parameters and their impact on the control circuit performance. The next sections in this chapter cover fundamental control concepts using a simple switch and other control circuits as examples for a more general overview of device modeling. The later sections in the chapter generalize the discussion to include other control circuits such as attenuators and phase shifters.

1.1.1 Simplified Switch Concepts

The basic concept of the switch depends on the location of the control element and its impedance Z_{CTL} in the control circuit. For a series-connected switch element, low impedance Z_{low} is required for the low loss or on-state, whereas a high impedance Z_{high} is required for the high loss or off-state. For a shunt-connected switch element, the opposite is true: a high impedance is required for the on-state and a low impedance for the off-state. In an ideal series-connected mechanical switch, these two impedance states would correspond to the switch contacts touching with very small resistance $Z_{low} = R_{ON}$ between the contacts; the open switch would then have infinite resistance. However, while this may be true at dc, in the open-switch condition, the two air-separated contacts (or vacuum or other gas, depending on the switch type) would create a capacitance C_{OFF} that is a function of the area and the contact separation distance. This capacitance exhibits a reactance of $1/j\omega C_{OFF}$ (ω is the radian frequency) and would show a frequency dependent loss in the off-state, with the loss decreasing with increasing frequency (although still infinite at dc, unless the dc bias voltage were large enough to cause breakdown in the medium between the contacts). In the off-state, there will be a small resistance in series with this capacitance, R_{OFF}, because of the finite conductivity and dimensions of the