MODELING AND CHARACTERIZATION OF RF AND MICROWAVE POWER FETS

This is a book about the compact modeling of RF power FETs. In it, you will find descriptions of characterization and measurement techniques, analysis methods, and the simulator implementation, model verification, and validation procedures that are needed to produce a transistor model that can be used with confidence by the circuit designer. Written by semiconductor industry professionals with many years' device modeling experience in LDMOS and III–V technologies, this is the first book to address the modeling requirements specific to high-power RF transistors.

A technology-independent approach is described, addressing thermal effects, scaling issues, nonlinear modeling, and in-package matching networks. These are illustrated using the current market-leading high-power RF technology, LDMOS, as well as with III–V power devices. This book is a comprehensive exposition of FET modeling, and is a must-have resource for seasoned professionals and new graduates in the RF and microwave power amplifier design and modeling community.

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To our families: Ljubica & Luka; Sandra, Andrea & Gaby; Gayle, Diane & Audrey.

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Peter H. Aaen, Jaime A. Pl´a And John Wood
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Preface

This is a book about the modeling of RF power transistors, in particular, field effect transistors, or FETs. In it, we shall describe characterization and measurement techniques, analysis and synthesis methods, the model implementation in the simulator, and the verification and validation techniques that are needed to produce a transistor model that can be used with confidence by the circuit designer.

The demand for accurate transistor models for RF and microwave circuit design has increased as a result of the more stringent requirements that are placed upon power amplifier and transmitter designs by the customers and regulating agencies. Modern power amplifiers for communications systems are tightly specified in terms of the required linearity performance, multichannel capability, bandwidth, and so forth. At the same time, there is a quest for higher-efficiency operation, to be realized perhaps by inherently nonlinear modes of operation, such as Class D, E, F, and others. These demands are generally conflicting, and the designer is faced with a multidimensional compromise. The traditional high-frequency design approaches of 'cut-and-try' are simply not appropriate for the design of RF power amplifiers for complex signal communications systems, and the designer must turn to computer-aided design (CAD) techniques and circuit simulation to optimize his design to meet the specifications. This increased use of CAD methods for RF power amplifier design places a greater reliance on the availability of accurate transistor models for simulation.

Transistor models have been used extensively in the design of analogue circuits, from lower-frequency multi-function circuits with hundreds to thousands of transistors, to higher-frequency microwave and millimeter-wave circuits with a relatively low transistor density. Simulation-based design is essential in these arenas: the circuits are virtually impossible to tune after manufacture, and so the design must be close to perfect first time, meaning that accurate models are essential.

The combination of high powers and high frequencies in RF and microwave power amplifiers brings together a unique set of challenges for the modeling engineer. The transistors themselves are physically large, and may be a significant fraction of a wavelength, even at microwave frequencies, for power transistors; the electrical behaviour in this distributed environment must be captured in the model. Even with the trend towards higher efficiency modes of operation, the device will generate a lot of heat, which must be dissipated effectively; the thermal effects on the transistor's electrical behaviour need to be characterized and modeled accurately to enable high-power designs.

Our goal is to produce compact models of the power FETs that can be used in the RF circuit simulator. The compact models will be designed to preserve the dynamics of the transistor, while being simple to develop and extract. We shall adopt a technology-independent approach to creating the compact model, based on observations of the transistor's electrical behaviour: the models will be derived directly from electrical and thermal measurements, and so careful characterization is necessary. We shall address the thermal effects on the device, scaling issues, nonlinear modeling of the active transistor, and the modeling of the internal package and matching networks. These modeling techniques are illustrated using LDMOS FETs, as this is the current market-leading high-power technology for RF cellular infrastructure applications, as well as with GaAs power devices. This is the first book to address the modeling requirements specific to high-power RF transistors. That said, the methodology that we outline can be applied to almost any FET modeling application.

We shall introduce the book by reviewing some of the historical developments in both applications and device technology that have resulted in transistor devices capable of delivering tens to hundreds of watts at RF and microwave frequencies. We shall also review the basics of FET operation, although we have left the detailed physical principles to the semiconductor device texts, and introduce the concepts behind compact modeling. This provides a basis for our analysis and construction of the transistor model in later parts of the book.

Accurate measurements form the foundation of the model. We describe how calibration and fixturing are used to ensure that repeatable and accurate measurements of the high-power transistor are made. A range of DC and RF measurement techniques and principles is outlined, for both model extraction and validation measurements. The analysis and construction of the compact model are then described. We partition the transistor into passive and active components, and address the modeling of these elements in detail.

The passive components comprise the transistor package and the in-package bondwire and capacitor components that provide the internal matching network of the transistor. This matching network is used to control the impedances presented at the terminals of the packaged transistor. The strict specifications imposed by the regulatory authorities require careful design of these matching networks. Consequently, these networks must be equally carefully modeled, to provide an accurate description of the transistor for circuit design.

The active transistor can then be accessed by de-embedding the package elements. We shall construct a large-signal model of the FET from DC and RF measurements, using a charge conservative approach for highest accuracy. The development of the charge conservative model is described in some detail, to give some insight into how the model works and its advantages for large-signal nonlinear applications.

The thermal environment is, of course, very important for power transistors: as the device heats up, its electrical properties change and so we spend some time describing a number of modern techniques for measuring the static and dynamic thermal properties. The thermal description is then used to construct a self-consistent electro-thermal model for the power FET.

At this point we consider how the model can be constructed in the circuit simulator, using function approximation or data fitting techniques, and how we can verify that the model is working correctly. Finally, we compare the model predictions with high-power RF measurements, using loadpull and large-signal network analyzer instruments, to validate the model accuracy and provide the circuit designers with confidence in its use.

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The production of this book has not been carried out in isolation. We have had a great deal of support from our friends and colleagues, and we would like to take this opportunity to acknowledge their help.

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