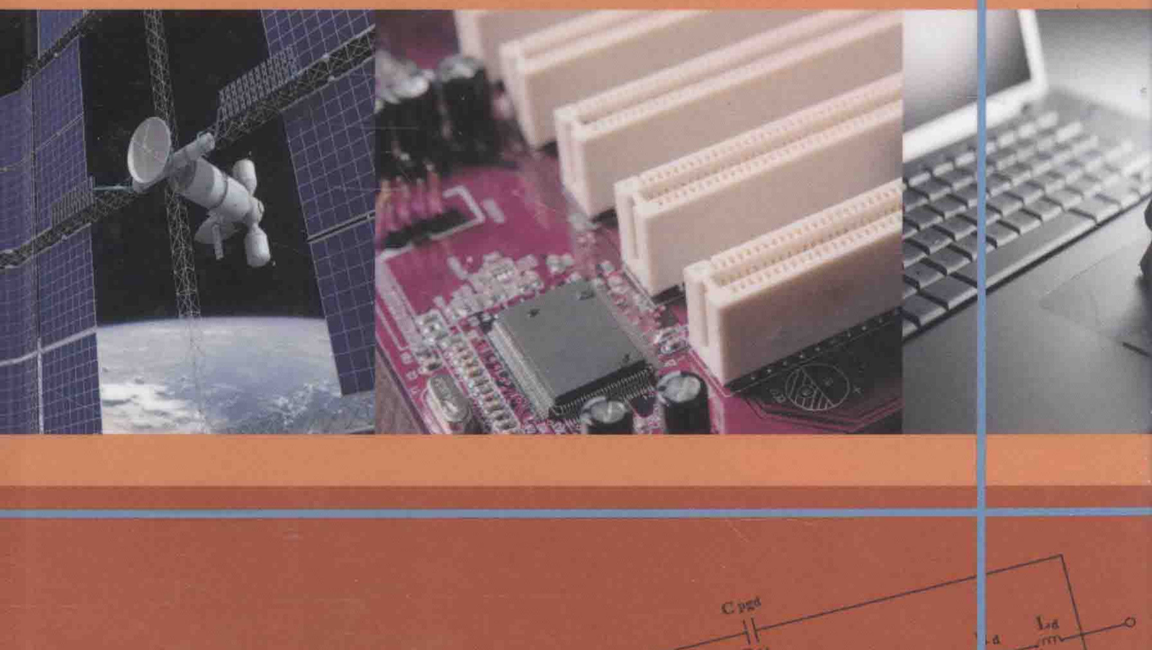
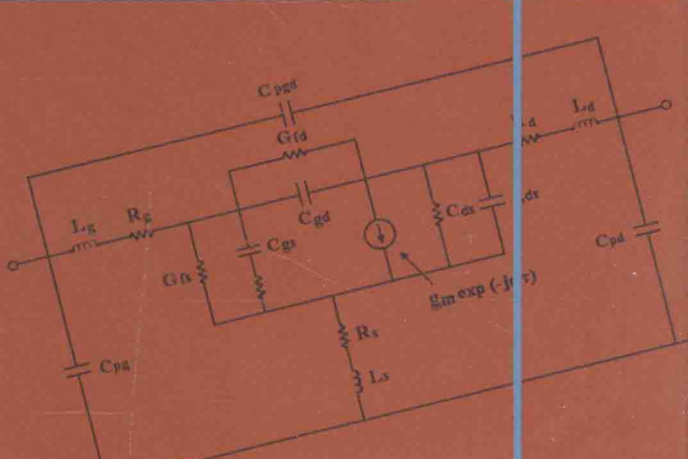
RF AND MICROWAVE MODELING AND MEASUREMENT TECHNIQUES FOR FIELD EFFECT TRANSISTORS





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To my wife Dongyan and son Hanqi for the lost hours and to my parents for their unquestioning support.

Preface

Radio and microwave compound field-effect transistors (FETs), such as metal semiconductor field effect transistors (MESFETs), and heterojunction field effect transistors (HFETs), which include high electron mobility transistors (HEMTs) and pseudomorphic high electron mobility transistors (PHEMTs), extend the advantages of silicon counterparts to significantly higher frequencies. This advanced performance of FETs is attractive for high-frequency circuit design in view of a system-on-a-chip realization, where digital, mixed-signal baseband, and radio frequency (RF) transceiver blocks would be integrated on a single chip.

Accurate microwave and RF measurement techniques are the basis of characterization of the microwave and RF devices along with the corresponding model parameter extraction. Existing books on microwave and RF devices traditionally lack a thorough treatment of the high-frequency measurement techniques. The primary objective of the present book is to bridge the gap between device modeling and state-of-the-art microwave measurement technique.

This book combines both measurement technique and its application in an example of compound semiconductor FETs. The book shows an approach on how to do the measurement and based on the measurement data, to start the small signal, nonlinear modeling, and parameter extraction for the devices. The book includes all detailed information for FETs, which seldom appears in other books like this, so this should be helpful for new researchers to make their way in their career. Even for those without a good microwave background, the contents of this book can be easily understood. The presentation of this book assumes only a basic course in electronic circuits as a prerequisite. Instead of using electromagnetic fields as most of the microwave engineering books do, the subject is introduced via circuit concepts.

This book is intended to serve as a reference book for practicing engineers and technicians working in the areas of RF, microwave and solid-state device, optoelectronic integrated circuit design. The book should also be useful as a text-book for RF and microwave courses designed for senior undergraduate and first-year graduate students. Especially in student design projects, we foresee that this book will be a valuable handbook as well as a reference, both on basic modeling issues and on specific FET models encountered in circuit simulators. For a senior course, chapters 4-7 are complementary to active microwave courses.

It is hoped that this book will offer the type of practical information necessary for use in today's complex and rapidly changing RF and microwave circuit design.

Contents

Chapter 1

Introduction

1.1 Overview of III–V Compound Semiconductor Devices

There are a wide variety of solid-state device technologies available for implementing microwave and radio frequency (RF) integrated circuits (ICs). The common used semiconductors are as follows [1–11]:

1. Silicon-based bipolar junction transistors (BJTs)
2. Silicon-based mental-oxide semiconductor field effect transistors (MOSFETs)
3. Silicon-based laterally diffused metal-oxide field-effect transistors (LDMOSFETs)
4. Silicon germanium heterojunction bipolar transistors (SiGe HBTs)
5. Gallium arsenide based metal semiconductor field-effect transistors (GaAs MESFETs)
6. Gallium arsenide high electron mobility transistors (GaAs HEMTs)
7. Gallium arsenide heterojunction bipolar transistors (GaAs HBTs)
8. Indium phosphide high electron mobility transistors (InP HEMTs)
9. Indium phosphide heterojunction bipolar transistors (InP HBTs)

Semiconductor material systems can be categorized into silicon-based and III–V-compound-semiconductor-based devices. Silicon-based semiconductor devices, with their low-cost, high-volume production, have improved frequency response significantly as the channel length is made smaller and up to 45 nm. In contrast, compound semiconductor-based devices take advantages of their intrinsic material properties and offer superior device performance in high-frequency applications such as monolithic microwave integrated circuits (MMICs). The III–V semiconductor industries have also increased their production yield and integration scale in response to the increasing demand of RF circuits in terrestrial and mobile wireless communications.

Alternatively, in terms of the operation mechanism, microwave and RF semiconductors can be categorized into field-effect transistors and bipolar transistors.

Table 1.1 Comparison of FET and Bipolar Transistor

Parameters	FET/HEMT	BJT/HBT
Physical dimension limitation	Gate length	Base and collector thickness
Turn-on characteristics	Gate threshold voltage	Base-emitter voltage
Output current density	Medium	High
Input impedance controller	Gate voltage	Base current
Noise-source	Gate-induced noise. Channel current noise. Low frequency noise. Gate leakage current noise.	Shot noise. Low-frequency noise.
Processing complexity	Medium	High

Table 1.1 shows the comparison of some device parameters for both FET and bipolar transistor devices [1]. First, the physical dimension limitation sets the ultimate device speed performance. Fundamentally, a shorter gate length in an FET can reduce the carrier transport time and a narrower base as well as thinner collector in a bipolar device can decrease the carrier transit time. Device turn-on characteristics of an HBT are controlled by a material band gap or the turn-on voltage in the base-emitter junction. In contrast, the pinchoff voltage of an FET depends on the doping and thickness of active channel. Typically, the noise sources in FET devices include gate-induced noise, channel current noise, low-frequency noise, gate leakage current noise, and thermal noise sources generated from the extrinsic resistances. For bipolar transistors, the noise figures are determined by shot noise, which is related to the operating currents.

Depending on applications, it is preferable that device have some of the following features [1]:

1. Maximum power gain bandwidth
2. Minimum noise figure
3. Maximum power-added efficiency (PAE)

4. Low thermal resistance
5. High temperature of operation and reliability
6. High linearity
7. Low leakage current under cutoff operation
8. Low-frequency noise
9. Multi functionality, low single-power supply
10. Semi-insulating substrate, mature technology, low cost

Different RF/microwave circuits require different transistor parameters. For example, power amplifiers (PAs) use transistors with higher power densities; low-noise amplifiers (LNAs) employ transistors with low-noise characteristics. A qualitative performance summary of each device technology is listed in Table 1.2 [9]. In most designs, the minimum noise figure, maximum power gain, and stability factor voltage standing wave ratio (VSWR) usually do not occur at the same input/output impedance in the Smith chart. Therefore, the selection of bias point and input/output impedance is determined by the spec requirements of each component.

Table 1.2 A Comparison Chart for Different Device Technologies in Wireless Communication RF Transceiver Applications

Parameters	GaAs MESFET	GaAs HBT	GaAs HEMT	Si RF CMOS	SiGe HBT	InP HBT
Device speed	Good	Good	Good	Fair	Good	Excellent
Chip density	Low	High	Low	Low	High	High
Transconductance	Medium	High	High	Low	High	High
Device matching	Poor	Good	Poor	Poor	Good	Good
PAE	Medium	High	High	Medium	Medium	High
Linearity	High	High	High	Low	Medium	High
Low-frequency noise	Poor	Good	Poor	Poor	Good	Good
Breakdown voltage	High	High	High	Medium	Medium	High
Integration level	MSI, LSI	MSI,LSI	MSI,LSI	VLSI	LSI,VLSI	MSI,LSI

1.2 RF/Microwave Device and Circuit CAD

The application of modern computer-aided design (CAD) tools offers an improved approach. As the sophistication and accuracy of these tools improve, significant reductions in design cycle time can be realized. The goal is to develop CAD tools with sufficient accuracy that can achieve first pass design. The CAD tools need to be improved until the simulated and measured RF performance of the component being designed are in good agreement. This will permit the design to be completed, simulated, and fully tested by an engineer working at a computer workstation before fabrication is implemented. To achieve this goal, improved accuracy CAD tools are required.

There are two kinds of commercial RF and microwave CAD software: physical-based and equivalent circuit based CAD software. The physical-based CAD software as a starting point of analysis, considers fundamental equations of transport in semiconductors. The equivalent circuit-based CAD software addresses the issue of what needs to be known about the device in addition to its equivalent circuit to predict the noise performance. State-of-the-art CAD methods for active microwave circuits rely heavily on models of real devices. The model permits the RF performance of a device or integrated circuit to be determined as a function of process and device design information or of bias and RF operating conditions. Table 1.3 summarizes the semiconductor device models in the commercial RF/microwave CAD software, in most cases, BJT, MOSFET, and MESFET models are available. This book focuses on the III–V compound FET device modeling and measurement technique.

Table 1.3 Semiconductor Device Models in Commercial RF/Microwave CAD Software

Software	BJT	MOSFET	MESFET	HEMT	HBT
ADS	☑	☑	☑	☑	☑
Cadence	☑	☑	☑	☑	☑
MDS	☑	☑	☑	☑	
EESOF	☑	☑	☑	☑	☑
PSPICE	☑	☑	☑		
HSPICE	☑	☑	☑		

1.3 Organization of This Book

We will spend the rest of this book trying to convey the microwave and RF modeling and measurement techniques for FET devices. This book focuses on how to measure the microwave performance and to build the linear, nonlinear, and noise models for FET devices.

In Chapter 2, the concept of two-port networks is discussed. The reader is introduced to the characterization of two-port networks and its representation in terms of a set of parameters (impedance, admittance, hybrid, transmission, scattering, and chain-scattering parameters) that can be cast into a matrix format. The relationship between two-port and three-port networks is then illustrated.

Chapter 3 presents basic concepts of the commonly used microwave and RF measurement techniques, which include S parameters and noise and power measurements. The corresponding calibration methods for each measurement are also summarized. The signal and noise deembedding methods for microwave components and circuits in on-wafer and coaxial measurement systems are discussed in more detail.

In Chapter 4, we introduce the physical structure and operation concept of FET devices. The small signal modeling and parameter extraction method are described, especially determination methods for pad capacitances, feedline inductances, extrinsic resistances, and intrinsic elements. The scaling rules for intrinsic elements are given also.

The nonlinear models for FETs, which include the physics-based nonlinear model, table-based nonlinear model, and empirical equivalent-circuit-based model are introduced in Chapter 5, as well as compact modeling techniques.

Chapter 6 first deals with the noise modeling and parameter extraction methods for FETs, and then turns to the determination of noise parameters, including tuner-based and noise-figure-based methods.

Artificial neural network (ANN) is very useful for neural-based microwave computer-aided design, and for analytically unified dc, small signal, and nonlinear device modeling. In Chapter 7, the microwave nonlinear device modeling technique based on a combination of the conventional equivalent circuit model and ANN is presented.

Chapter 2

Representation of Microwave Two-Port Network

The microwave signal and noise matrix analysis techniques are the basis of representation of the microwave network, and are the important tools of the radio frequency (RF) and microwave semiconductor modeling and parameter extraction. RF and microwave device, circuit and components can be classified as one-, two-, three-, and N-port networks. A majority of circuits under analysis are two-port networks. Therefore we focus in this chapter primarily on two-port characterization and study its representation in terms of a set of parameters that can be cast into a matrix format. The definition of a two-port network is that a network that has only two access ports: one for input or excitation and one for output or response. This chapter introduces the important linear parameters (including signal and noise parameters) that are currently used to characterize two-port networks. These parameters enable manipulation and optimization.

2.1 Signal Parameters

There are several ways to characterize the two-port network. The most commonly used parameters are the impedance Z, admittance Y, hybrid H, transmission $ABCD$, scattering S, and chain scattering T parameters. These parameters are used to describe linear networks fully and are interchangeable. Conversion between them is often used as an aid to circuit design when, for example, conversion enables easy deconvolution of certain parts of an equivalent circuit. This is because the terminating impedance's and driving sources vary. Further, if components are added in parallel the admittance parameters can be directly added;

similarly, if they are added in series impedance parameters can be used. Matrix manipulation also enables easy conversion among for example, common base (gate), common emitter (source), and common collector (drain) configurations. The impedance Z, admittance Y, hybrid H, and transmission $ABCD$ normally are called the low-frequency signal parameters, and are based on the voltages and currents at each port. The scattering S and chain scattering T parameters normally are called the high-frequency signal parameters, and are based on traveling waves applied to a network. Each of them can be used to characterize linear networks fully, and all show a generic form. This chapter concentrates on two-port networks, though all the rules described can be extended to N-port devices. A two-port network based on the Z-, Y-, H-, and $ABCD$ parameters is shown in Figure 2.1. It can be seen that the two-port network has four port variables: V_1, V_2, I_1, and I_2. We can use two of variables as excitation variables and the other two as response variables.

2.1.1 Impedance Parameters

The open-circuit impedance parameters (i.e., Z parameters) characterization of two-port networks are based on the exciting the network by the voltage V_1 at input port and the voltage V_2 at output port. In this case I_1 and I_2 are the independent variables, and V_1 and V_2 are the dependent variables. The network operation can be described by the following two equations:

$$V_1 = Z_{11} \cdot I_1 + Z_{12} \cdot I_2 \tag{2.1}$$

$$V_2 = Z_{21} \cdot I_1 + Z_{22} \cdot I_2 \tag{2.2}$$

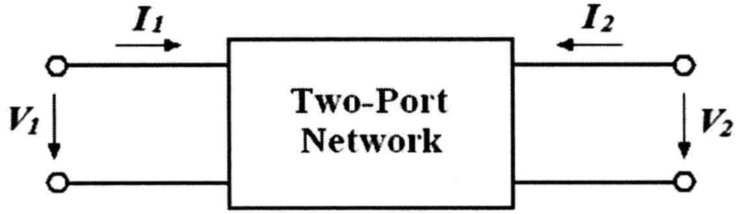

Figure 2.1 A block diagram of a two-port network

Using the matrix representation, we can write:

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \tag{2.3}$$

or

$$[V] = [Z][I] \tag{2.4}$$

where the $[Z]$ is called the impedance matrix of a two-port network. Since voltages V_1 and V_2 are in volts, and I_1 and I_2 are in amperes, the four parameters Z_{11}, Z_{12}, Z_{21}, and Z_{22} must be in ohms. Therefore, these are called impedance parameters, and their values completely characterize the linear two-port network. The definition equations and physical meaning of Z parameters are summarized in Table 2.1, and Figure 2.2 shows the corresponding equivalent circuit model of Z parameters. It is noted that the units of all Z parameters are in ohms (Ω).

The open circuits are not very easy to implement at a higher frequency range because of fringing capacitances; therefore, these parameters were measured only at low-frequency range. When measuring an active device or circuit, a bias network (or Bias-Tee) is required. This should still present an open-circuit at the signal frequency but of course should be a short circuit to the bias voltage. This would usually consist of a large inductor with a low series resistance.

2.1.2 Admittance Parameters

Now let us look at the short-circuit Y parameters where the voltages are the independent variables. These are called the short-circuit admit-

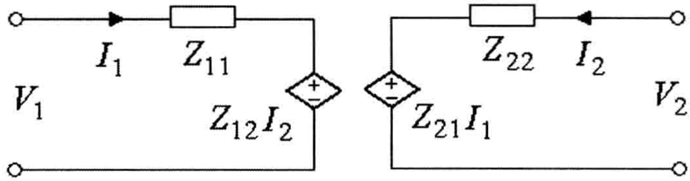

Figure 2.2 Equivalent circuit model for Z parameters