Market projections indicate that the sale of integrated circuits (IC) based on semiconductor devices will continue to show strong growth in the next few years, due to the significant reductions in price. This will allow the technology to be extended to a wider range of applications in microwave and radio frequency (RF) communication. To keep pace, the manufacturing technology for microwave and RF integrated circuit needs to migrate to one that can produce high volumes at a very low cost. One major problem is the accurate device modeling and high-level IC design.

This book provides a highly comprehensive summary on circuit-related modeling techniques and parameter extraction methods for heterojunction bipolar transistors (HBT), one of the most important devices for microwave applications. Appropriate for electrical engineering and computer science studies, the book starts with an introduction of signal and noise parameters of two-port networks and then covers the basic operation mechanisms and modeling techniques of bipolar junction transistor and HBT.

- An overview on modeling techniques and parameter extraction methods for HBTs focusing on circuit simulation and design
- A valuable reference to the basic modeling issues and specific semiconductor device models encountered in circuit simulators
- Details the accurate device modeling for HBTs and high-level IC design using HBTs
- Presents electrical/RF engineering-related theory and tools and includes equivalent circuits and their matrix descriptions, noise, small and large signal analysis methods.

Heterojunction Bipolar Transistors for Circuit Design: Microwave Modeling and Parameter Extraction is an outstanding reference book for engineers and technicians working in the areas of RF, microwave and solid-state device and IC design, and it is also of great interest to graduate/undergraduate students studying microwave active devices and circuits design.
HETEROJUNCTION BIPOLAR TRANSISTORS FOR CIRCUIT DESIGN
HETEROJUNCTION BIPOLAR TRANSISTORS FOR CIRCUIT DESIGN
MICROWAVE MODELING AND PARAMETER EXTRACTION

Jianjun Gao
East China Normal University
Shanghai, P.R. China
## Contents

About the Author ix  
Preface xi  
Acknowledgments xiii  
Nomenclature xv  

1 Introduction 1  
1.1 Overview of Heterojunction Bipolar Transistors 1  
1.2 Modeling and Measurement for HBT 5  
1.3 Organization of This Book 7  
References 7  

2 Basic Concept of Microwave Device Modeling 9  
2.1 Signal Parameters 10  
2.1.1 Low-Frequency Parameters 11  
2.1.2 S-Parameters 16  
2.2 Representation of Noisy Two-Port Network 21  
2.2.1 Noise Matrix 21  
2.2.2 Noise Parameters 24  
2.3 Basic Circuit Elements 25  
2.3.1 Resistance 25  
2.3.2 Capacitance 26
4 Basic Principle of HBT
4.1 Semiconductor Heterojunction
4.2 HBT Device
   4.2.1 GaAs HBT
   4.2.2 InP HBT
4.3 Summary
References

5 Small-Signal Modeling and Parameter Extraction of HBT
5.1 Small-Signal Circuit Model
   5.1.1 Pad Structure
   5.1.2 T-Type Circuit Model
   5.1.3 \( \pi \)-Type Circuit Model
   5.1.4 Unilateral Power Gain
   5.1.5 \( f_T \) and \( f_{\text{max}} \)
5.2 HBT Device Structure
5.3 Extraction Method of PAD Capacitances
   5.3.1 Open Test Structure Method
   5.3.2 Pinch-Off Method
5.4 Extraction Method of Extrinsuc Inductances
   5.4.1 Short Test Structure Method
   5.4.2 Open-Collector Method
5.5 Extraction Method of Extrinsuc Resistance
   5.5.1 Z Parameter Method
   5.5.2 Cold-HBT Method
   5.5.3 Open-Collector Method
5.6 Extraction Method of Intrinsic Resistance
   5.6.1 Direct Extraction Method
   5.6.2 Hybrid Method
5.7 Semianalysis Method
5.8 Summary
References

6 Large-Signal Equivalent Circuit Modeling of HBT
6.1 Linear and Nonlinear
   6.1.1 Definition
   6.1.2 Nonlinear Lumped Elements
6.2 Large Signal and Small Signal
6.3 Thermal Resistance
   6.3.1 Definition
   6.3.2 Equivalent Circuit Model
   6.3.3 Determination of Thermal Resistance
References
Jianjun Gao was born in Hebei province, P.R. China, in 1968. He received his B.E. and Ph.D. degrees from Tsinghua University, in 1991 and 1999, respectively, and M.E. degree from Hebei Semiconductor Research Institute in 1994.

From 1999 to 2001, he was a postdoctoral research fellow at the Microelectronics R&D Center, Chinese Academy of Sciences, developing PHEMT optical modulator driver. In 2001, he joined the School of Electrical and Electronic Engineering, Nanyang Technological University (NTU), Singapore, as a research fellow in semiconductor device modeling and wafer measurement. In 2003, he joined the Institute of High-Frequency and Semiconductor System Technologies, Berlin University of
Technology, Germany, as a research associate working on the InP HBT modeling and circuit design for high-speed optical communication. In 2004, he joined the Electronics Engineering Department, Carleton University, Canada, as a postdoctoral fellow working on the semiconductor neural network modeling technique. From 2004 to 2007, he was a full professor of radio engineering department at the South-east University, Nanjing, China. Since 2007, he has been a full professor at the School of Information Science and Technology, East China Normal University, Shanghai, China. He authored *RF and Microwave Modeling and Measurement Techniques for Field Effect Transistors* (SciTech Publishing, 2009) and *Optoelectronic Integrated Circuit Design and Device Modeling* (Wiley, 2010).

His main areas of research are characterization, modeling, and wafer measurement of microwave semiconductor devices, optoelectronics devices, and high-speed integrated circuit for radio frequency and optical communication.

Readers can refer to http://faculty.ecnu.edu.cn/gaojianjun/Info_eng.html for further details about of the author.
Preface

This textbook is written for beginners learning about the characterization of heterojunction bipolar transistors. My purposes are as follows:

• To describe the basic modeling techniques for semiconductor devices
• To introduce the basic concepts of heterojunction bipolar transistor
• To provide state-of-the-art modeling and equivalent circuit parameter extraction methods for heterojunction bipolar transistor

Appropriate for electrical engineering and computer science, this book starts with an introduction of signal and noise parameters of two-port networks and then covers the basic operation mechanisms and modeling techniques for bipolar junction transistor and heterojunction bipolar transistor; the corresponding equivalent circuit model parameter extraction methods are introduced in detail. Readers can understand this book without a good grounding in microwave theory and concepts. The presentation of this book assumes only a basic course in electronic circuits as a prerequisite.

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 devices, and integrated circuit designs. The book should also be useful as a textbook for microwave active device and circuit 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 optoelectronic device models encountered in circuit simulators.
The reference list at the end of each chapter is more elaborate than what is common for a typical textbook. The listing of recent research papers should be useful for researchers using this book as a reference. At the same time, students can benefit from it if they are assigned problems requiring reading of the original research papers.
I would like to thank Prof. Law Choi Look and Hong Wang of Nanyang Technical University (Singapore), Prof. Georg Boeck of Berlin Technical University (Germany), and Prof. Qi-Jun Zhang of Carleton University at Ottawa (Canada) for their cooperation.

I would also like to thank my family for their great support, patience, and understanding provided throughout the period of writing.

This book was supported in part by the National Natural Science Foundation of China under Grants 61176036 and 61474044, and Shanghai Minhang Excellent Talents.
Nomenclature

nm  nanometer  one-billionth of a meter (=10^{-9} m)
µm  micrometer  one-millionth of a meter (=10^{-6} m)
ps  picosecond  one-thousandth of a billionth of a second (=10^{-12} s)
MHz terahertz  1 million vibrations per second (=10^{6} Hz)
GHz gigahertz  1 billion vibrations per second (=10^{9} Hz)
mW  milliwatt  one-thousandth of a watt (=10^{-3} W)
q   electronic charge (=1.6 × 10^{-19} C)
k  Boltzmann’s constant (=1.38 × 10^{-23} J/k)
fF femto farad  one-billionth of a farad (=10^{-15} F)
Gb/s 1 billion bits per second (=10^9 bits/second)
pF  pico farad  one-thousandth of a billionth of a farad (=10^{-12} F)
pH  pico henry
AlGaAs aluminum gallium arsenide
AC alternating current
BJT bipolar junction transistors
BiCMOS bipolar complementary metal-oxide semiconductor field-effect transistor
CAD computer-aided design
CB common base
CC common collector
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>CE</td>
<td>common emitter</td>
</tr>
<tr>
<td>CPW</td>
<td>coplanar waveguide</td>
</tr>
<tr>
<td>CW</td>
<td>continuous wave</td>
</tr>
<tr>
<td>DA</td>
<td>distributed amplifier</td>
</tr>
<tr>
<td>DC</td>
<td>direct current</td>
</tr>
<tr>
<td>DHBT</td>
<td>double heterojunction bipolar transistor</td>
</tr>
<tr>
<td>DUT</td>
<td>device under test</td>
</tr>
<tr>
<td>ECL</td>
<td>emitter-coupled logic</td>
</tr>
<tr>
<td>eV</td>
<td>electron-volts</td>
</tr>
<tr>
<td>GaAs</td>
<td>gallium arsenide</td>
</tr>
<tr>
<td>GSBME</td>
<td>gas-source molecular beam epitaxy</td>
</tr>
<tr>
<td>HB</td>
<td>harmonic balance</td>
</tr>
<tr>
<td>HBT</td>
<td>heterojunction bipolar transistor</td>
</tr>
<tr>
<td>HEMT</td>
<td>high electron mobility transistor</td>
</tr>
<tr>
<td>HICUM</td>
<td>high current model</td>
</tr>
<tr>
<td>InGaAs</td>
<td>Indium gallium arsenide</td>
</tr>
<tr>
<td>InP</td>
<td>Indium phosphide</td>
</tr>
<tr>
<td>I–V</td>
<td>current–voltage</td>
</tr>
<tr>
<td>LNA</td>
<td>low-noise amplifier</td>
</tr>
<tr>
<td>LRM</td>
<td>line-reflect-match</td>
</tr>
<tr>
<td>MAG</td>
<td>maximum available gain</td>
</tr>
<tr>
<td>MBE</td>
<td>molecular beam epitaxy</td>
</tr>
<tr>
<td>MESFET</td>
<td>metal semiconductor field-effect transistor</td>
</tr>
<tr>
<td>MEXTRAM</td>
<td>most exquisite transistor model</td>
</tr>
<tr>
<td>MMIC</td>
<td>microwave-integrated circuit</td>
</tr>
<tr>
<td>MOCVD</td>
<td>molecular organic chemical vapor deposition</td>
</tr>
<tr>
<td>MOSFET</td>
<td>metal-oxide semiconductor field-effect transistor</td>
</tr>
<tr>
<td>NMS</td>
<td>noise measurement system</td>
</tr>
<tr>
<td>PA</td>
<td>power amplifier</td>
</tr>
<tr>
<td>PCB</td>
<td>printed circuit board</td>
</tr>
<tr>
<td>RF</td>
<td>radio frequency</td>
</tr>
<tr>
<td>RFIC</td>
<td>radio frequency-integrated circuit</td>
</tr>
<tr>
<td>SHBT</td>
<td>single heterojunction bipolar transistor</td>
</tr>
<tr>
<td>SGP</td>
<td>SPICE Gummel–Poon</td>
</tr>
<tr>
<td>SI</td>
<td>semi-isolation</td>
</tr>
<tr>
<td>SiGe</td>
<td>silicon germanium</td>
</tr>
<tr>
<td>GSG</td>
<td>ground–signal–ground</td>
</tr>
<tr>
<td>SPICE</td>
<td>simulation program with integrated circuit emphasis</td>
</tr>
<tr>
<td>VBIC</td>
<td>vertical bipolar intercompany</td>
</tr>
<tr>
<td>VNA</td>
<td>vector network analyzer</td>
</tr>
<tr>
<td>VSWR</td>
<td>voltage-standing wave ratio</td>
</tr>
</tbody>
</table>
1

Introduction

1.1 Overview of Heterojunction Bipolar Transistors

Semiconductor material systems can be categorized into silicon-based and III–V compound semiconductor-based devices [1, 2]. 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 22 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. Alternatively, in terms of transistor operation principles, semiconductor transistor technologies can be categorized into two major types depending on their physical carrier transportation mechanisms: field effect transistors (FETs) and bipolar transistors. The bipolar transistors include bipolar junction transistors (BJTs) and heterojunction bipolar transistors (HBTs).

Table 1.1 shows the comparison of some device parameters for both FET and bipolar transistor devices [3–5]. FETs are majority carrier devices with lateral current conduction, while bipolar transistors are the vertical devices that allow the electron and hole conduction. The speed of the bipolar transistor device is determined by the transit time through the thin vertical base–collector (B–C) layers. The maximum speed of the FET is determined by a transit time and is controlled by the gate length defined by the lithographic techniques. FET devices are also referred
as unipolar devices because the majority carriers are in principle responsible for the transport characteristics. Drain current in an FET is modulated by gate voltage through channel width modulation scheme. The amplification process in FET is characterized by a transconductance to assess the controllability of the gate voltage modulation over the output drain current. On the other hand, the collector current in bipolar transistor is modulated by the minority current injection from the base. Bipolar transistor is equivalent to a current amplifier as the input base current is “amplified” by a factor of current gain through the transistor and the output current is “collected” at the collector end.

There are wide varieties of the HBT device technologies available for the implementation of microwave and radio frequency integrated circuits (RFICs). The commonly used HBT devices are as follows:

1. Gallium arsenide-based heterojunction bipolar transistors (GaAs HBTs)
2. Indium phosphide-based heterojunction bipolar transistors (InP HBTs)
3. Silicon–germanium-based heterojunction bipolar transistors (SiGe HBTs)

III–V compound HBTs (GaAs HBTs and InP HBTs) largely retain the advantages of their Si predecessors but extend them to higher frequencies. Additionally, a variety of disadvantages of Si bipolar transistors can be overcome. HBTs in the GaAs/AlGaAs material system have been the first beneficiaries of the improved materials. These devices are now becoming available commercially and are poised for application in a wide variety of high-performance circuits. HBTs enjoy several advantages over their conventional silicon cousins [6]. These include:

- A thinner base and lower base resistance which yields higher gain, cutoff frequency, and maximum oscillation frequency
- Higher transconductance due to the exponential output current to input voltage variation

<table>
<thead>
<tr>
<th>Table 1.1</th>
<th>Comparison of FET and bipolar transistor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
<td>Field effect transistor</td>
</tr>
<tr>
<td>Physical structure</td>
<td>Lateral structure</td>
</tr>
<tr>
<td>Physical dimension limitation</td>
<td>Gate length</td>
</tr>
<tr>
<td>Scalable factor</td>
<td>Gate width</td>
</tr>
<tr>
<td>Turn-on characteristics</td>
<td>Gate threshold voltage</td>
</tr>
<tr>
<td>Input impedance controller</td>
<td>Gate voltage</td>
</tr>
<tr>
<td>Low frequency noise</td>
<td>High</td>
</tr>
<tr>
<td>RF noise source</td>
<td>Gate-induced noise</td>
</tr>
<tr>
<td>Output current density</td>
<td>Channel current noise</td>
</tr>
<tr>
<td>Processing complexity</td>
<td>Gate leakage current noise</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
</tr>
</tbody>
</table>

Heterojunction Bipolar Transistors for Circuit Design
High power density since the entire emitter area can carry the current because of the low emitter resistance

- High breakdown voltage
- Lower 1/f noise
- Low parasitics

A cross section of a simple HBT is shown in Figure 1.1. In a single heterojunction device, the base, collector, and subcollector will all be of the same material, such as GaAs, while in the AlGaAs system (double heterojunction device (DHBT)), for example, a small mole fraction of aluminum is added to the emitter to increase the bandgap. HBT operation involves the following three steps [7]: (i) minority carrier injection from emitter to base, (ii) carrier transport in the base region, and (iii) carrier collection at the B–C junction. In normal operation (forward bias), electrons are injected from emitter into base crossing over the heterostructure barrier. For an abrupt heterojunction barrier, the electron injection is due to thermionic emission, while for a graded base–emitter (B–E) junction, the electrons diffuse to the base. The C–B junction is reverse biased, and the high electric field present in the space charge region is responsible for collection of electrons in the collector terminal.

The detailed layer structure for GaAs/AlGaAs HBTs grown by molecular organic chemical vapor deposition (MOCVD) is shown in Figure 1.2. The dopants used are silicon for n type and carbon for p type. The sequence of growth starts with the $n^+$-GaAs subcollector layer on a (100) semi-insulating GaAs substrate, followed by an n-GaAs collector layer. The $p^+$-GaAs base layer is then grown followed by $N$-AlGaAs emitter. The final layer is $n^+$-GaAs emitter contact layer. The emitter layer consists of a high-doped ($5 \times 10^{18}$ cm$^{-3}$) GaAs cap and a wide bandgap Al$_{0.3}$Ga$_{0.7}$As layer. The cap layer is used to produce low-resistivity emitter ohmic contact. The doping and thickness of Al$_{0.3}$Ga$_{0.7}$As layer are chosen to minimize the emitter resistance and E–B capacitance while maximizing reverse breakdown voltage.

The InP-based HBTs offer the advantages over GaAs HBTs of a low turn-on voltage, higher electron mobility, better thermal dissipation, and better microwave
performance while still obtaining a high collector-to-base breakdown voltage. The InP HBTs have been used successfully to implement complex digital ICs for 40 Gb/s optical communication. The InP HBTs used in this book were grown by gas-source molecular beam epitaxy (GSMBE) on semi-insulating (100) InP substrates supplied by a commercial vendor. Be and Si are used for p- and n-type dopants, respectively. The detailed layer structure of the InP/InGaAs/InP DHBT is shown in Table 1.2 [8]. An InGaAs/InP composite collector structure with a dipole doping at the InGaAs/InP interface is employed to avoid current blocking effect. The devices were fabricated with a triple mesa process with different emitter

![Figure 1.2](image-url)  

**Figure 1.2** Cross section of GaAs/AlGaAs HBT

<table>
<thead>
<tr>
<th>Layers</th>
<th>Thickness (nm)</th>
<th>Doping</th>
</tr>
</thead>
<tbody>
<tr>
<td>InGaAs cap</td>
<td>100</td>
<td>$n^+ = 2 \times 10^{19}$ cm$^{-3}$</td>
</tr>
<tr>
<td>InP cap</td>
<td>60</td>
<td>$n^+ = 2 \times 10^{19}$ cm$^{-3}$</td>
</tr>
<tr>
<td>InP emitter</td>
<td>90</td>
<td>$n = 3 \times 10^{17}$ cm$^{-3}$</td>
</tr>
<tr>
<td>InGaAs base</td>
<td>47</td>
<td>$p^+ = 2 \times 10^{19}$ cm$^{-3}$</td>
</tr>
<tr>
<td>Collector</td>
<td></td>
<td></td>
</tr>
<tr>
<td>InGaAs</td>
<td>40</td>
<td>$n^- = 5 \times 10^{15}$ cm$^{-3}$</td>
</tr>
<tr>
<td>InGaAs</td>
<td>10</td>
<td>$p = 2 \times 10^{18}$ cm$^{-3}$</td>
</tr>
<tr>
<td>InP</td>
<td>10</td>
<td>$n = 1 \times 10^{18}$ cm$^{-3}$</td>
</tr>
<tr>
<td>InP</td>
<td>290</td>
<td>$n^- = 5 \times 10^{15}$ cm$^{-3}$</td>
</tr>
<tr>
<td>InP subcollector</td>
<td>8</td>
<td>$n^+ = 5 \times 10^{18}$ cm$^{-3}$</td>
</tr>
<tr>
<td>InGaAs subcollector</td>
<td>450</td>
<td>$n^+ = 5 \times 10^{18}$ cm$^{-3}$</td>
</tr>
<tr>
<td>SI substrate</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1.2 Epitaxial structure of InP/InGaAs/InP DHBT
size. Nonalloyed Ti/Pt/Au were used for emitter, base, and collector ohmic contacts. Gold-electroplated air bridges were then used to connect the emitter, base, and collector contacts to the external wire-bonding pads.

Compared to the III–V compound semiconductor devices, the silicon-based device offers the advantages of low cost, high integration, and the possibility of a single-chip solution [9]. Compared with III–V compound devices, silicon has numerous practical advantages as a semiconductor material, including the following [10]: (i) an extremely high-quality dielectric (SiO₂) can be trivially grown on Si and used for isolation; (ii) ease of growth of large, low-cost, defect-free crystals; (iii) ease of doping and fabrication of ohmic contacts; (iv) Si has excellent thermal properties allowing for the efficient removal of dissipated heat; (v) Si has excellent mechanical strength, facilitating ease of handling and fabrication; and (vi) it is easy to make very low-resistance ohmic contacts to Si. By using strained and composition-graded SiGe as the base layer in conventional Si BJTs, SiGe HBTs achieved RF performance comparable to GaAs technologies with fabrication cost and reliability similar to the Si process. A silicon-based device has intrinsically higher thermal conductivity than III–V-based HBTs, and the SiGe HBT offers the flexibility of bandgap engineering as well as base and emitter doping adjustment capabilities when compared with Si BJTs. The processing compatibility of SiGe technology and existing Si CMOS provides a powerful combination for future high-frequency mix-signal circuits. A qualitative performance summary of each device technology is listed in Table 1.3.

### 1.2 Modeling and Measurement for HBT

The analysis and design of integrated circuits are dependent heavily on the utilization of suitable models for circuit components (i.e., passive and active devices). This is true in hand analysis, where fairly simple models are generally used, and in computer-aided design (CAD) software, where more complex models are encountered. In the electronic world, highly advanced CAD tools exist for the design, analysis, and simulation of nearly every aspect of integration, ranging from
process to device to circuit to system. The application of modern 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 is 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. In order 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 softwares. 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 and/or bias and RF operating conditions. The equivalent circuit device models must be based upon accurate parameter extraction from experimental data. The model permits the RF performance of a device or integrated circuit to be determined as a function of process and device design information and/or bias and RF operating conditions.

Microwave and RF measurement techniques are the basis of characterization of the microwave and RF devices and circuits. The microwave and RF integrated circuits also need verification using microwave and RF measurements. It is noted that unlike the coarse measurement, the microwave and RF measurement techniques are the high-accuracy measurements, for example, small error will cause the large discrepancy for the semiconductor device modeling and parameter extraction, and the corresponding RF ICs designed by using the device model mentioned previously. Figure 1.3 shows the relationship between device modeling, microwave measurement, and circuit design.

![Figure 1.3](image-url)  Relationship between modeling and measurement
1.3 Organization of This Book

We will spend the rest of this book trying to convey the microwave and RF modeling and parameter extraction techniques for bipolar devices (BJTs and HBTs). The focus of this book will be how to measure the microwave performance and build the linear, nonlinear, and noise models for bipolar devices.

In Chapter 2, the basic concept of semiconductor device modeling 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, and scattering parameters) that can be cast into a matrix format. The de-embedding procedure for semiconductor device parameter extraction is then illustrated.

In Chapter 3, we introduce the physical structure and operation concept of PN junctions and use the theory developed for the PN junction in the analysis of the bipolar transistor. Considering the various BJT models, we restrict our discussion to only the most popular types such as the Ebers–Moll model and Gummel–Poon model.

Based on the analysis of BJT, an introduction to the basic concepts concerning the heterojunction is provided in Chapter 4. The complete analysis of heterojunction structures involves quantum mechanics and detailed calculation is introduced, and the physical structure and operation concept of the GaAs HBTs and InP HBTs are reviewed. In Chapter 5, the small-signal modeling and parameter extraction methods for GaAs HBTs and InP HBTs are described. The relationship between linear and nonlinear models for HBTs is discussed in Chapter 6 and empirical equivalent circuit-based models are described briefly. Chapter 7 deals with the noise modeling and parameter extraction method for HBTs, and the determination of noise parameters including tuner-based and noise figure-based methods is introduced. Chapter 8 presents the physical structure and operation concept of SiGe HBT, and the corresponding small-signal models and large-signal models are introduced.

In Chapter 9, basic concepts of the commonly used microwave and RF measurement techniques have been introduced and the setup of DC and S-parameter on-wafer measurement system is then illustrated.

References


Almost each of microwave and radio-frequency (RF) active and passive components can be regarded as a two-port network. Two-port equivalent circuit model is widely used in circuit design to describe the electrical behavior of both active and passive devices. The semiconductor device modeling concept is that the complex active device is represented as a two-port circuit which includes the basic circuit elements, such as resistances, inductances, capacitances, and controlled sources (see Figure 2.1). From equivalent circuit model, the circuit designer can easily understand the operation mechanism of the complex active device. The microwave signal and noise matrix analysis techniques are the basis of representation of the microwave networks and the important tools of the RF and microwave semiconductor modeling and parameter extraction. We will focus primarily on two-port characterization and will 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 a network that has only two access ports, one for input or excitation and one for output or response.

In this chapter, we will:

- Introduce the important linear parameters (including signal and noise parameters)
- Discuss the interconnection of two-port networks
- Determine the signal and noise network parameters of basic circuit elements
- Analyze the deembedding techniques for parasitic elements
- Introduce parameter extraction techniques for basic circuit elements

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2.1 Signal Parameters

The most commonly used two-port network parameters are the impedance $Z$, admittance $Y$, hybrid $H$, transmission $ABCD$, and scattering $S$-parameters. 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 main reason is that the open and short circuits are not very easy to implement at higher frequency range owing to fringing capacitances, and therefore, these parameters were only ever measured at low-frequency range. The scattering $S$-parameters normally are called 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. A two-port network based on the $Z$-, $Y$-, $H$-, and $ABCD$-parameters is shown in Figure 2.2a. 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 the variables as excitation variables and the other two as response variables. Figure 2.2b shows a network along with the incident and reflected waves at its