

HEMTs and HBTs: Devices, Fabrication, and Circuits

Fazal Ali

Pacific Monolithics

Aditya Gupta

Westinghouse Electric Company

Editors

Artech House

Boston • London

Contents

Preface		xi
Chapter 1	HEMTs and HBTs: Introduction and Overview	
	Fazal Ali and Aditya Gupta	1
1.1	Introduction	1
1.2	High Electron Mobility Transistors (HEMTs)	3
1.3	Heterojunction Bipolar Transistors (HBTs)	5
1.4	Summary	8
Chapter 2	HEMT Device Physics and Models	Mukunda B. Das 11
2.1	Introduction	11
2.2	Carrier Transport in the HEMT Structure	13
	2.2.1 Band Diagram and 2-DEG in AlGaAs/GaAs Systems	14
	2.2.2 2-DEG Carrier Mobility and Saturation Velocity	18
	2.2.3 2-DEG Charge-Control by Schottky Barrier Gate	22
	2.2.4 Ohmic Contacts and Series Resistances	26
2.3	The Charge-Control Model	29
	2.3.1 dc and Small-Signal Characteristics	29
	2.3.2 Temperature Stability of Device Operation	36
	2.3.3 Low-Frequency (LF) Equivalent Network Model	39
	2.3.4 The Unity-Current-Gain Frequency	44
	2.3.5 Low-Frequency $1/f$ and $g-r$ Noise Sources	47
2.4	High-Frequency (HF) Limitations	51
	2.4.1 HF Equivalent Network for the Intrinsic HEMT	52
	2.4.2 Determination of Equivalent Network Parameters	57
	2.4.3 Power Gain and Stability	61
	2.4.4 HF Noise Sources and Performance of HEMTs	63
Chapter 3	HEMT Devices and Circuit Applications	P.C. Chao, Alan Swanson, April Brown, Umesh Mishra, Fazal Ali, and Cindy Yuen 77

3.1	Introduction	77
3.2	GaAs-Based Conventional HEMT	77
	3.2.1 Material Considerations	79
	3.2.2 Device Fabrication	84
	3.2.3 dc and RF Performance	91
	3.2.4 Outlook	99
3.3	GaAs-Based Pseudomorphic HEMT	103
	3.3.1 Material Structure	103
	3.3.2 Applications of Pseudomorphic HEMTs	111
3.4	InP-Based Pseudomorphic HEMT	123
	3.4.1 Introduction	123
	3.4.2 Material Properties and Growth	124
	3.4.3 Device Fabrication and Performance	134
	3.4.4 Circuit Performance	143
3.5	HEMT Analog Circuit Applications	148
	3.5.1 Introduction	148
	3.5.2 HEMT Low-Noise Amplifiers	148
	3.5.3 HEMT Wideband Amplifiers	150
	3.5.4 HEMT Power Amplifiers	159
	3.5.5 HEMT Control Circuits	163
	3.5.6 HEMT Mixers and Converters	168
	3.5.7 HEMT Oscillators	174
	3.5.8 HEMT Frequency Doublers	175
	3.5.9 Device Testing	177
	3.5.10 Conclusion	182
3.6	HEMT Reliability	184
	3.6.1 Reliability Testing of Low-Noise HEMTs	184
	3.6.2 Reliability of Low-Noise HEMTs	186
	3.6.3 Summary	188
Chapter 4	HBT Device Physics and Models Mukunda B. Das	191
4.1	Introduction	191
4.2	Carrier Transport in HBT Structures	195
	4.2.1 Band Diagram and Current Transport	196
	4.2.2 Recombination Processes	200
	4.2.3 Drift, Diffusion, and Saturation Velocity	202
	4.2.4 Ohmic Contacts and Series Resistances	204
4.3	The Charge-Control Model	206
	4.3.1 dc and Small-Signal Characteristics	207
	4.3.2 LF Equivalent Network Model and Unity Current Gain Frequency	212
	4.3.3 The Switching Limitations	215
	4.3.4 Low-Frequency $1/f$ Noise and $g-r$ Noise Sources	219

4.4	High Frequency Limitations	224
4.4.1	HF Two-port Parameters and Equivalent Network Model	224
4.4.2	Determination of the Equivalent Network Parameters	228
4.4.3	Power Gain and Stability	234
4.4.4	HF Noise Sources and Noise Figures	236
4.4.5	Power Density Limitations of HBTs	241
4.4.6	Comparison of HBTs and HEMTs	246
Chapter 5	HBT Devices and Circuit Applications	
	Michael E. Kim, Burhan Bayraktaroglu, and Aditya Gupta	253
5.1	Introduction	253
5.1.1	Comparison with GaAs MESFET and HEMT	257
5.1.2	Comparison with Advanced Silicon Bipolar Transistor	258
5.2	Device Structure	260
5.2.1	Epitaxial Layer Growth	266
5.2.2	Emitter-up <i>versus</i> Collector-up	269
5.3	HBT Fabrication Technology	270
5.3.1	Self-Aligned Contacts	274
5.3.2	Planar Structures	276
5.3.3	Representative HBT IC Process	278
5.4	Technology Characterization	281
5.4.1	HBT dc Characteristics	282
5.4.2	HBT High-Frequency Characteristics	286
5.4.3	Intrinsic HBT Linearity	287
5.4.4	Intrinsic HBT Nonlinearity	287
5.4.5	HBT Noise Performance	290
5.4.6	Schottky Diode Characteristics	291
5.4.7	Thin-Film Resistors	291
5.4.8	Metal-Insulator-Metal (MIM) Capacitors	292
5.4.9	HBT Device Modeling and Simulation	292
5.4.10	Technology Qualification	292
5.5	Power HBT Design Considerations	301
5.5.1	Collector Design	301
5.5.2	Device Impedance	302
5.5.3	Size Considerations	304
5.5.4	Thermal Considerations	307
5.5.5	HBT Scaling	311
5.5.6	HBT Monolithic Amplifiers	316
5.5.7	HBT Complementary Amplifiers	318
5.6	Circuit Applications	322

5.6.1	Analog and Microwave Applications	328
5.6.2	Microwave Oscillators	333
5.6.3	Digital Applications	341
5.6.4	Analog-to-Digital Conversion Applications	345
5.6.5	Monolithically Combined Microwave-Digital Applications	352
5.7	InP-Based HBT	354
5.8	Reliability	361
Index		371