



CENTRO DE
INVESTIGACIÓN
DOCUMENTARIA

HANDBOOK OF SEMICONDUCTOR ELECTRONICS

A PRACTICAL MANUAL COVERING THE PHYSICS, TECHNOLOGY,
AND APPLICATIONS OF TRANSISTORS, DIODES, AND OTHER
SEMICONDUCTOR DEVICES IN CONVENTIONAL
AND INTEGRATED CIRCUITS

edited by **LLOYD P. HUNTER**

*Professor of Electrical Engineering
University of Rochester, Rochester, New York*



Third Edition

McGRAW-HILL BOOK COMPANY

New York St. Louis San Francisco London Sydney
Toronto Mexico Panama

Contents

Contributors *v*

Preface *vii*

List of Symbols *xxiii*

Part 1 PHYSICS OF SEMICONDUCTOR MATERIALS, DEVICES, AND CIRCUITS

Section 1. Semiconductor Devices

1.1	Historical Introduction	1-4
1.2	Single-junction Devices	1-8
1.2a	The Rectifier	1-8
1.2b	The High-speed Switch	1-8
1.2c	Voltage-regulator (Zener) Diode	1-9
1.2d	Esaki Tunnel Diode	1-9
1.2e	Double-base Junction Diode	1-9
1.2f	Variable-capacitance (Varactor) Diode	1-9
1.2g	Photodiode	1-9
1.2h	Schottky-barrier Diode	1-10
1.2i	Light-emitting Diode	1-10
1.2j	Injection Laser	1-10
1.3	Two-junction Bipolar Devices	1-10
1.3a	The Diffusion Transistor	1-10
1.3b	The Drift Transistor	1-11
1.3c	Phototransistor	1-11
1.3d	Double-base Junction Transistor	1-11
1.4	Transistor Fabrication Types	1-12
1.4a	Alloy Transistors	1-12
1.4b	Mesa Transistor	1-12
1.4c	Surface-barrier Transistor	1-12
1.4d	Planar Passivated Transistor	1-12
1.4e	Epitaxial Transistor	1-13
1.5	Field-effect Transistor	1-13
1.5a	Junction-type FET	1-13
1.5b	Insulated-gate or MOS-type FET	1-14
1.6	Three-junction Devices	1-15
1.6a	Controlled Rectifier	1-15
1.6b	Thyratron Transistor	1-15
1.7	Integrated Circuits	1-17

Section 2. Electronic Conduction in Solids

2.1	Atoms, Molecules, and Crystals	2-1
2.2	Insulators, Conductors, and Semiconductors	2-4

2.3	Fields and Energy Bands	2-5
2.4	Impurities in Semiconductors	2-7
2.5	Thermal Excitation and the Fermi Level	2-9
2.5a	The Concept of Mobility	2-14
2.6	Optical Excitation	2-15
2.6a	The Concept of Lifetime	2-15
2.6b	Photoconductivity	2-16
2.7	Low-temperature Conductivity	2-19
2.7a	Impurity-band Conduction	2-19
2.7b	Impact Ionization of Impurities	2-20
2.8	Radiation Effects	2-20
Section 3. Rectification, Diodes, and Photocells		
3.1	Barriers	3-2
3.1a	Metal-semiconductor Contacts (Schottky Barrier)	3-2
3.1b	PN Junctions	3-4
3.2	Rectification	3-6
3.3	Minority-carrier Injection and Diffusion	3-10
3.4	The Diode Equation	3-12
3.4a	Effects of the Energy Gap	3-14
3.4b	Avalanche Multiplication and Breakdown	3-15
3.5	Minority-carrier Recombination and Lifetime	3-17
3.5a	Traps and Regeneration	3-17
3.5b	Sensitization of Photoconductors	3-19
3.6	Diodes	3-21
3.6a	Rectifiers	3-23
3.6b	Switching Diodes and Recovery Time	3-24
3.6c	Varactor Diodes	3-26
3.6d	Avalanche Diodes	3-29
3.6e	Mixer Diode	3-31
3.7	The Tunneling Phenomenon	3-32
3.7a	Esaki Tunnel Diode	3-33
3.7b	"Backward" Diode	3-36
3.7c	Zener Diode	3-37
3.8	The Photovoltaic Effect	3-38
3.9	Photocells	3-42
3.9a	Polycrystalline Films	3-42
3.9b	PN-junction Photocells	3-45
3.9c	Light Levels	3-47
3.9d	Spectral Sensitivity	3-48
3.10	Light-emitting Diodes	3-48
3.10a	Stimulated Emission	3-49
3.10b	Injection Lasers	3-50
3.11	Ohmic Contacts	3-53
3.11a	Minority-carrier Exclusion	3-54
3.12	Heterojunctions	3-54
3.13	Gunn-effect Oscillator	3-57
Section 4. Transistor Action		
4.1	The Diffusion Analysis of the Transistor	4-2
4.1a	Emitter Injection Efficiency γ	4-4
4.1b	Transport Efficiency β	4-7

4.1c	Collector Saturation Current I_{CO}	4-8
4.1d	Collector Efficiency α	4-9
4.1e	Collector Junction Avalanche Multiplication M	4-10
4.1f	Other Effects of Voltage and Current on α	4-10
4.1g	The Continuity Equation	4-12
4.1h	The Admittance of the Ports	4-14
4.2	The Generalized Transistor Equations	4-16
4.3	The Transistor as a Switch	4-18
4.3a	Transient Behavior and Charge Control	4-19
4.3b	Speed of Response	4-20
4.3c	Offset Voltage	4-23
4.3d	On-Off Resistance Ratio	4-24
4.4	Frequency Response	4-25
4.4a	Frequency Variation of α_{FB}	4-26
4.4b	Diffusion Capacitance	4-28
4.4c	Transit-time Effects	4-28
4.4d	Collector Capacitance and Base Resistance	4-29
4.5	The Drift Transistor	4-30
4.5a	Transit-time Effects	4-31
4.5b	Diffusion Capacitance	4-33
4.6	The Field-effect Transistor	4-34
4.6a	Junction Type	4-34
4.6b	Insulated-gate (MOS) Type	4-37
4.6c	The FET as a Switch	4-39
4.7	Four-region Transistor	4-39
4.7a	The "Hook-collector" Transistor	4-40
4.7b	The NPN Diode	4-41
4.7c	Controlled Rectifier	4-42
4.7d	The Thyatron Transistor	4-44
4.7e	The Phototransistor	4-44
4.8	Transistor Structural Effects	4-44
4.8a	The Planar Passivated Transistor	4-44
4.8b	The Uses of Epitaxy	4-45
4.8c	The Double-base Diode	4-47
4.8d	The Tetrode Transistor	4-48
4.8e	The Surface-barrier Transistor	4-49
4.9	The Avalanche Transistor	4-50
4.10	Temperature Effects	4-51
4.11	Degeneracy Effects	4-52
4.11a	High-level Injection	4-52

Section 5. Physical Effects Involved in Integrated-circuit Combinations

5.1	Classification of Integrated Circuits	5-2
5.1a	The Monolithic-circuit Structure	5-2
5.1b	The Hybrid-circuit Structure	5-5
5.2	Monolithic Bipolar Transistors	5-6
5.2a	The Collector Region	5-6
5.2b	The Base and Emitter Regions	5-9
5.2c	Complementary Transistors	5-9
5.2d	Parasitic Capacitance	5-11
5.3	Monolithic Junction Diodes	5-12
5.3a	The Emitter Junction Diodes	5-12

5.3b	The Collector Junction Diodes	5-13
5.3c	The Parallel Emitter-Collector Junction Diode	5-14
5.4	Monolithic FET Devices	5-15
5.4a	The Junction FET	5-15
5.4b	The Insulated-gate FET	5-17
5.4c	The FET Current Limiter	5-19
5.4d	The FET Biased Resistor	5-19
5.5	Monolithic Passive Elements	5-19
5.5a	The Diffused Resistor	5-19
5.5b	The Junction Capacitor	5-21
5.5c	Thin-film Resistors and Capacitors	5-22
5.6	Hybrid-circuit Devices	5-24

Part 2 TECHNOLOGY OF SEMICONDUCTOR MATERIALS, DEVICES, AND CIRCUITS

Section 6. Preparation of Semiconductor Materials

PART 1 *Bulk Crystalline Material*

6.1	Introduction	6-4
6.2	Chemical Purification of the Basic Materials	6-4
6.2a	The Production of Pure Germanium	6-4
6.2b	The Production of Pure Silicon	6-6
6.2c	The Preparation of Pure Gallium and Pure Arsenic	6-7
6.3	Zone Refining	6-8
6.3a	Theoretical Considerations	6-8
6.3b	Applications	6-11
6.3c	Zone Refining of Germanium	6-12
6.3d	Zone Refining of Silicon	6-14
6.4	Growing of Single Crystals	6-18
6.4a	Control of Resistivity, Theoretical Considerations	6-18
6.4b	Control of Physical Perfection, Theoretical Considerations	6-21
6.4c	Applications	6-22
6.4d	Growing of Germanium Single Crystals	6-23
6.4e	Growing of Silicon Single Crystals	6-26
6.4f	Growing of Gallium Arsenide Single Crystals	6-30

PART 2 *Thin-film Crystalline Material*

6.5	Epitaxial Growth of Thin Films	6-32
6.5a	Introduction	6-32
6.5b	Mass Transport	6-33
6.5c	Crystal Perfection	6-38
6.5d	Crystal Orientation; Heteroepitaxy	6-45
6.5e	Impurity Control	6-46
6.5f	Processes	6-49
6.5g	Evaluation of Epitaxial-film Properties	6-54

Section 7. PN Junction Formation Techniques

7.1	Introduction	7-2
7.2	Production of PN Junctions by Doping	7-3
7.2a	The Split-reservoir Method	7-5
7.3	Rate Growing	7-5

7.4	Remelt and Segregation Junctions	7-5
7.5	Alloy or Fusion Junctions	7-6
7.5a	Material for Alloy Junctions	7-7
7.5b	Details and Control of the Alloy Process	7-8
7.5c	Alloy Junctions on Silicon	7-10
7.6	Diffused Junctions.	7-10
7.6a	Diffusion Theory	7-10
7.6b	Impurity Distributions	7-11
7.6c	Deviations from Simple Theory	7-12
7.6d	Selection of Diffusion Impurity	7-17
7.6e	Diffusion Techniques	7-24
7.6f	Diffusion in Compound Semiconductors	7-36
7.6g	Application of Diffusion Techniques.	7-38
7.7	Deposited PN Junctions	7-43
7.7a	Theory of Epitaxial Growth	7-43
7.7b	Techniques of Vapor Growth.	7-44
7.7c	Vapor-growth Systems	7-50
7.7d	Characteristics of Vapor-grown Films	7-53
7.7e	Application of Vapor-growth Techniques	7-55
7.8	Ion Implantation	7-56
7.8a	Theory	7-57
7.8b	Structural Considerations	7-58
7.8c	Application	7-60

Section 8. Techniques of Circuit Integration

8.1	Introduction	8-1
8.2	Monolithic-circuit Integration	8-3
8.2a	Photoengraving.	8-3
8.2b	Oxidation for Diffusion Masking.	8-7
8.2c	Silicon Dioxide Properties	8-11
8.2d	Metal-film Interconnections	8-14
8.2e	Process Example	8-16
8.3	Monolithic Thin-film Circuits	8-20
8.4	Hybrid-circuit Integration	8-22
8.4a	Multiple-chip Hybrid Circuits	8-22
8.4b	Thick-film Hybrid Circuits	8-25
8.4c	Beam-lead Interconnection	8-26
8.5	Large-scale Integration	8-30

Section 9. Encapsulation

9.1	Introduction	9-1
9.2	Reasons for Encapsulation	9-2
9.2a	Economy in Handling and Assembly	9-2
9.2b	Mechanical Protection.	9-2
9.2c	Metallurgical Stability	9-3
9.2d	Surface Stability	9-4
9.2e	Thermal Management.	9-4
9.2f	Testing	9-6
9.3	Encapsulation Technology	9-6
9.3a	Packageless Components	9-6
9.3b	Metal-insulator Subassemblies	9-7
9.3c	Metal-to-Metal Final Seals	9-9

9.3d	Glass-to-Glass Final Seals	9-10
9.3e	Glass-to-Ceramic Final Seals	9-10
9.3f	Plastic Encapsulation	9-10
9.3g	Molded Assemblies	9-11
9.4	Package Types	9-11
9.4a	Some Packages in Common Use	9-12
9.5	Reliability Testing	9-22

Section 10. Design of Monolithic Linear Circuits

10.1	Integrated-circuit Components	10-2
10.1a	PNP Transistors	10-3
10.1b	Supergain Transistors	10-4
10.1c	Resistors	10-6
10.1d	Field-effect Transistors	10-7
10.1e	Breakdown Diodes	10-7
10.1f	Capacitors	10-8
10.1g	Junction Leakages	10-9
10.2	Circuit-design Techniques	10-10
10.2a	Biasing Circuits	10-10
10.2b	Active Collector Loads	10-11
10.2c	Low-current Techniques	10-14
10.2d	Temperature Compensation	10-17
10.3	Operational Amplifiers	10-23
10.3a	Reducing Input Currents	10-25
10.3b	Fast Amplifiers	10-28
10.4	Conclusions	10-31

Part 3 CIRCUIT DESIGN AND APPLICATION OF SEMICONDUCTOR DEVICES

Section 11. Low-frequency Amplifiers

11.1	Transistor Equivalent Circuits	11-4
11.1a	Linear Two-port Network Representations	11-4
11.1b	Small-signal Transistor Parameters	11-8
11.1c	Transistor Circuit Models	11-10
11.1d	Circuit-model Interrelations	11-13
11.1e	Characteristics of Typical Transistors	11-14
11.1f	Parameter Dependence on Operating Point and Temperature	11-16
11.1g	Large-signal Analysis	11-17
11.2	Biasing and Operating-point Stability	11-20
11.2a	Selection of Operating Point	11-20
11.2b	Mechanisms Causing Shift in Operating Point	11-22
11.2c	Operating-point Stability Factors	11-28
11.2d	Practical Bias Circuits	11-30
11.2e	Direct-coupled Stages	11-36
11.2f	Temperature-compensation Techniques	11-38
11.2g	Bias-circuit Design Examples	11-41
11.2h	Thermal Runaway	11-44
11.3	Small-signal (Linear) Amplifiers	11-47
11.3a	Significance of Low-frequency Restriction	11-47
11.3b	Amplifier Representation as Terminated Two-port Network	11-47
11.3c	Parameter Modification to Absorb External Impedances	11-52
11.3d	Multistage (Cascade) Amplifier Parameters	11-55

11.3e	Characteristics of Typical One- and Two-stage Transistor Amplifiers	11-58
11.3f	Amplifier Frequency Response	11-65
11.3g	Considerations for Integrated-circuit Amplifier Design	11-71
11.3h	Characteristics of Typical Integrated-circuit Amplifiers	11-71
11.4	Large-signal (Power) Amplifiers	11-75
11.4a	Transistor Maximum Ratings	11-75
11.4b	Thermal Resistance and Heat Transfer	11-79
11.4c	Large-signal Amplifier Characteristics	11-80
11.4d	Series-fed Class A Amplifiers	11-86
11.4e	Shunt-fed Class A Amplifiers	11-88
11.4f	Class B Amplifiers	11-93
11.4g	Push-Pull Amplifiers	11-96
11.4h	Transformerless Amplifier Circuits	11-102
11.4i	Complementary-symmetry Amplifier Configurations	11-105
11.4j	Amplifier Power-supply Requirements	11-108
11.5	Feedback Amplifiers	11-110
11.5a	Network Representation of Linear Feedback Amplifiers	11-110
11.5b	Effect of Feedback on Gain and Bias Stability	11-116
11.5c	Effect of Feedback on Frequency Response and Impedance Levels	11-117
11.5d	Specific Feedback-amplifier Configurations	11-119
11.5e	Feedback-amplifier Performance Example	11-122
11.5f	Design Requirements for Closed-loop Stability	11-123
11.5g	Integrated-circuit Feedback Amplifiers	11-127
11.5h	Feedback for Distortion Reduction in Large-signal Amplifiers	11-130
11.6	Noise in Low-level Amplifiers	11-131
11.6a	Noise Figure and Signal-to-Noise Ratio	11-131
11.6b	Effective Noise Bandwidth	11-136
11.6c	Noise Figure of Multistage (Cascade) Amplifiers	11-138
11.6d	Noise-figure Measurement	11-139
11.6e	Noise Characteristics of Typical Transistors	11-141
11.6f	Transistor Noise Equivalent Circuit	11-143
11.6g	Considerations for Low-noise Amplifier Design	11-147
11.7	Selected Low-frequency Amplifier Circuits	11-148
11.7a	Manual Gain Control Circuits	11-148
11.7b	Automatic Gain Control Circuits	11-149
11.7c	Bandpass R-C Feedback Amplifier	11-150
11.7d	High-gain Differential Amplifier	11-151
11.7e	Frequency-response Shaping Circuits	11-152
11.7f	Phase-inverter Circuits	11-154

Section 12. High-frequency and Video Amplification

12.1	Available Alternatives	12-2
12.2	Transistor Comparisons	12-4
<i>Bipolar Transistor High-frequency Parameters</i>		
12.3	Transit Time	12-8
12.3a	Base Transit Time	12-9
12.3b	Depletion-layer Transit Time	12-12
12.4	Depletion-layer Transition Capacitances	12-12
12.4a	Emitter Transition Capacitance	12-12
12.4b	Collector Transition Capacitance	12-13

12.5	Lead Impedance	12-14
	12.5a Base Resistance	12-15
	12.5b Collector Body Resistance	12-15
	12.5c Emitter Body Resistance	12-15
	12.5d Lead Inductance	12-15
12.6	Equivalent-circuit Representations	12-16
	12.6a The Intrinsic Transistor	12-16
	12.6b The Complete Transistor	12-18
12.7	Dependence of High-frequency Properties on Bias Point	12-19
	12.7a Emitter-current Effects	12-19
	12.7b Collector-voltage Effects	12-20
12.8	Noise Figure	12-20
	12.8a Midband Noise Figure	12-22
	12.8b High-frequency Noise Figure	12-23
	12.8c The Corner Frequency	12-24
	12.8d Optimum Source Resistance	12-25
	12.8e Minimum Noise Figure versus Frequency	12-25
	12.8f Biasing for Minimum Noise Figure	12-26
12.9	Temperature Dependence at High Frequency	12-26
12.10	Two-port Scattering-parameter Representation	12-27
12.11	High-frequency Figures of Merit	12-29
	12.11a The Characteristic Frequency f_T	12-29
	12.11b The Maximum Frequency of Oscillation f_{max}	12-31
12.12	Gain Characterization	12-32
<i>Video Amplifiers</i>		
12.13	Single-stage Video Amplifiers	12-35
	12.13a Common Emitter	12-35
	12.13b Common Base	12-37
12.14	Multistage Video Amplifiers	12-38
12.15	Gain-Bandwidth Trade	12-39
	12.15a Alternating Feedback Cascade	12-41
	12.15b Voltage-controlled Current Stage	12-42
<i>Bandpass Amplifiers</i>		
12.16	High-frequency Circuits	12-46
12.17	Interstages	12-47
12.18	Unilateralization (Neutralization)	12-48
	12.18a Imperfect Neutralization	12-50
	12.18b Fixed Neutralization	12-52
	12.18c Unneutralized Stages	12-53
12.19	Circuit-design Considerations	12-54
12.20	Input and Output Impedance	12-55
	12.20a Input Impedance	12-55
	12.20b Output Impedance	12-58
	12.20c Effects of Neutralization	12-61
12.21	Interstage Losses	12-61
12.22	Bandwidth of Tuned Amplifiers	12-64
12.23	Gain Control of Tuned Amplifiers	12-67
	12.23a AGC and Intermodulation	12-68
12.24	High-frequency Power Amplification	12-72
Section 13. D-C Amplifiers		
13.1	Introduction	13-1
13.2	Noise	13-2
	13.2a Noise in the Bipolar Junction Transistor	13-2

13.2b	Noise in the Junction-gate Field-effect Transistor	13-6
13.2c	Noise in the Metal-insulator Semiconductor Transistor (J-FET)	13-6
13.3	The Effects of Temperature on Pertinent Device Parameters	13-7
13.3a	The Temperature Dependence of the Bipolar Transistor	13-7
13.3b	The Temperature Dependence of the Junction-gate Field-effect Transistor	13-10
13.3c	The Temperature Dependence of the Insulated-gate Field-effect Transistor	13-11
13.4	The Direct-coupled D-C Amplifier	13-12
13.5	The Modulated-input D-C Amplifier	13-16
13.5a	The Bipolar Transistor as a Switch	13-18
13.5b	The Field-effect Transistors as Switches	13-19
13.5c	The Photoconductor Modulator	13-19
13.6	The Stability and Aging Effects of Semiconductor Devices	13-20
13.7	Appendix	13-21

Section 14. Transistor Oscillators

Sinusoidal Oscillators

14.1	Circuits Using One Transistor	14-3
14.1a	Common-base Circuits	14-3
14.1b	Bias Arrangements	14-4
14.1c	Common-emitter Circuits	14-5
14.1d	Common-collector Circuits	14-5
14.1e	Circuits with No External Feedback	14-5
14.1f	Series-tuned Circuits	14-5
14.1g	Circuits with Distributed Feedback	14-6
14.2	Unified Approach to Oscillator Design	14-6
14.2a	The Oscillation Condition	14-7
14.2b	Transformer Feedback	14-7
14.2c	Feedback without Transformers	14-8
14.2d	Equilibrium of Oscillations— <i>h</i> -parameter Analysis	14-8
14.2e	Transistor Configurations	14-10
14.2f	The Transistor Equivalent Circuit	14-10
14.2g	Maximum Oscillation Frequency	14-12
14.2h	Design Expressions for Small-signal Equilibrium	14-13
14.2i	Maximum Potential Instability	14-13
14.3	Design of Limiting Conditions	14-14
14.3a	Class A Oscillation	14-16
14.3b	Class C Oscillation	14-20
14.3c	Multiple Oscillations	14-21
14.4	Oscillator Stability	14-21
14.4a	Amplitude Stability	14-21
14.4b	Frequency Stability	14-22
14.4c	Crystal-controlled Oscillators	14-22
14.4d	Temperature-stabilized Crystal-controlled Oscillators	14-23
14.5	Modulation of a Transistor Oscillator	14-24
14.6	Oscillator Transient Conditions	14-24
14.7	Push-Pull Circuits	14-24
14.8	R-C Phase-shift Oscillators	14-25

Nonsinusoidal Oscillators

14.9	Relaxation Oscillators	14-27
14.10	Blocking Oscillators	14-27
14.11	Multivibrators	14-29

Section 15. Transistor Switching Circuits

15.1	Bipolar-transistor Characteristics	15-3
15.2	FET Characteristics	15-6
15.3	Diode Characteristics	15-7
15.4	Passive-component Characteristics	15-8
15.5	Design Criteria Techniques	15-9
	15.5a Steady State	15-9
	15.5b Transient	15-11
	15.5c Stability	15-13
	15.5d Design Techniques	15-14
<i>Circuit Building Blocks</i>		
15.6	Input Stages	15-14
15.7	The Saturating Inverter/Gain Stages	15-14
	15.7a D-C Requirements	15-15
	15.7b Transient Response	15-16
	15.7c Rise Time	15-17
	15.7d Storage Time	15-18
	15.7e Fall Time	15-19
	15.7f Off-level Stabilization	15-19
	15.7g Minority-carrier Storage	15-19
	15.7h Using Nonlinear Feedback	15-20
15.8	Output Stages—Emitter Follower	15-21
	15.8a Steady-state Conditions	15-22
	15.8b Transient Response	15-24
	15.8c Push-Pull Output Stages	15-27
<i>Logic Circuits</i>		
15.9	Popular Bipolar Logic Circuits	15-28
	15.9a Resistor Transistor Logic (RTL)	15-28
	15.9b Direct-coupled Transistor Logic (DCTL) Circuits	15-30
	15.9c Diode-Transistor Logic (DTL)	15-40
	15.9d Transistor-Transistor Logic (TTL or T ² L)	15-44
	15.9e Emitter-follower Logic	15-44
	15.9f Current-mode Logic (CML)	15-45
15.10	Popular FET Logic Circuits	15-49
	15.10a FET Direct-coupled Transistor Logic	15-49
	15.10b Multiphase FET Circuits	15-50
	15.10c Complimentary FET Circuits	15-50
<i>Triggers</i>		
15.11	Bistable Flip-flops	15-52
	15.11a Requirements for Saturated-off Operation	15-52
	15.11b Resetting the Trigger	15-52
	15.11c Binary Operation	15-54
	15.11d Transient Operation	15-55
15.12	Monostable Circuits	15-56
	15.12a Single Shots	15-56
	15.12b Blocking Oscillator	15-57
15.13	Esaki Tunnel Diode Circuits	15-59
	15.13a Transient Response	15-60
	15.13b Tunnel Diode-Transistor Circuits	15-63
	15.13c Twin Tunnel-diode Circuits	15-64

15.14	Summary	15-68
-------	-------------------	-------

Section 16. Microwave Applications

16.1	Introduction	16-1
16.2	Tunnel-diode Devices	16-2
	16.2a Impedance of Tunnel Diodes	16-3
	16.2b Tunnel-diode Amplifiers	16-3
	16.2c Tunnel-diode Oscillators	16-6
	16.2d Tunnel-diode Frequency Converters	16-10
16.3	Varactor Devices	16-11
	16.3a Parametric Amplifiers and Frequency Converters	16-14
	16.3b Harmonic Generation	16-17
16.4	Microwave Transistors	16-19
	16.4a Transistor Circuits	16-19
	16.4b Harmonic Generation	16-20
16.5	Bulk Devices	16-21
	16.5a Transferred-electron Devices	16-21
	16.5b Avalanche Transit-Time Diodes	16-26
16.6	Point-contact and Schottky-barrier Diodes	16-28
16.7	PIN Diodes	16-30

Section 17. Power Supplies

17.1	Classification of Power Supplies	17-2
17.2	Unregulated A-C to D-C Power Supplies	17-3
	17.2a Rectification	17-5
	17.2b Filters	17-6
	17.2c Multiplier Circuits	17-12
17.3	Unregulated D-C to A-C Power Supplies—Inverters	17-14
	17.3a Principles of Inverters	17-15
	17.3b Transistor Inverters	17-15
	17.3c Silicon-controlled-rectifier Inverters	17-26
	17.3d Tunnel-diode Inverters	17-31
	17.3e Sine-wave Inverters	17-32
	17.3f Sine-wave Synthesis	17-32
17.4	Regulated Power Supplies—Nonswitching	17-35
	17.4a Series Regulators	17-38
	17.4b Voltage and Current Regulators	17-42
	17.4c Sampling Elements	17-42
	17.4d References	17-43
	17.4e Error Amplifiers	17-46
	17.4f Pass Elements	17-48
	17.4g Integrated-circuit Regulators	17-50
17.5	Regulated Power Supplies—Switching	17-50
	17.5a Main Regulators	17-50
	17.5b Preregulators	17-53
	17.5c Stacked Regulators	17-54
17.6	Regulator Features	17-55
	17.6a Remote Sensing and Programming	17-55
	17.6b Overload Protection and Indication	17-56
	17.6c Constant-voltage to Constant-current Changeover	17-56
17.7	Power-supply Systems	17-58
	17.7a Auto-series Connection	17-58

17.7 <i>b</i>	Auto-parallel Connection	17-58
17.7 <i>c</i>	Auto-tracking Operation	17-59
17.7 <i>d</i>	Interlocked Turn-on Turn-off Operation	17-60
17.8	Cooling of Power Devices	17-61
17.8 <i>a</i>	Device Thermal Parameters	17-61
17.8 <i>b</i>	Device to Heat Sink Considerations	17-61
17.8 <i>c</i>	Natural-convection Cooling	17-61
17.8 <i>d</i>	Forced-convection Cooling	17-63
17.8 <i>e</i>	Other Methods of Cooling	17-64

Section 18. Switching in Instrumentation and Control

18.1	Scope	18-1
18.2	States of a Switch	18-2
18.3	Schottky-barrier Diode	18-3
18.4	Step-recovery Diode	18-6
18.4 <i>a</i>	General Application	18-10
18.4 <i>b</i>	Impulse Generator	18-12
18.4 <i>c</i>	Square-wave Generator	18-13
18.5	Tunnel Diode	18-14
18.5 <i>a</i>	Monostable Trigger	18-15
18.6	Avalanche Transistor	18-20
18.7	Thyristor	18-22

Part 4 MEASUREMENT AND ANALYTICAL TECHNIQUES

Section 19. Semiconductor-device Measurements

19.1	Static Curves and Display	19-4
19.1 <i>a</i>	Point-by-Point and D-C Methods	19-4
19.1 <i>b</i>	Visual Display	19-4
19.1 <i>c</i>	Oscillation and Noise Suppression	19-5
19.1 <i>d</i>	Thermal Effects	19-6
19.1 <i>e</i>	D-C Parameter Conventions	19-7
19.2	Limits of Device Operation	19-8
19.2 <i>a</i>	Reverse Breakdown	19-9
19.2 <i>b</i>	Collector-Emitter Breakdown	19-10
19.2 <i>c</i>	Punch-through	19-10
19.2 <i>d</i>	Maximum Power Dissipation	19-11
19.2 <i>e</i>	Second Breakdown	19-13
19.2 <i>f</i>	Gain Variation with Current Level	19-14
19.2 <i>g</i>	Voltage Saturation	19-14
19.3	Large-signal Parameters for PN-junction Devices—Transistors	19-15
19.3 <i>a</i>	Transition-layer Capacitances	19-15
19.3 <i>b</i>	Base Resistance	19-16
19.3 <i>c</i>	The h_{ie} Method of Measuring Base Resistance	19-17
19.3 <i>d</i>	The Base-resistance Collector-capacitance Product $r_b C_c$	19-17
19.3 <i>e</i>	Sheet-resistance Method	19-18
19.3 <i>f</i>	Intrinsic Parameters	19-18
19.3 <i>g</i>	Charge-control Parameters	19-18
19.3 <i>h</i>	Precautions for the Use of Transistor Models	19-20

19.3i	Saturation	19-20
<i>Diodes</i>		
19.3j	The Long-base-diode Lifetime	19-21
19.3k	Diode Series Resistance	19-22
19.3l	Recovered Charge	19-23
19.4	Small-signal Parameters	19-23
19.4a	One-port (Driving-point) Admittances	19-26
19.4b	Transadmittances	19-29
19.4c	Short-circuit Current Transfer Ratio (current gain)	19-31
19.5	Figures of Merit	19-35
19.5a	The Frequency f_r	19-35
19.5b	Recirculating Loop Frequency	19-36
19.6	Testing Integrated Devices	19-37
19.6a	Sequential and Nonsequential Testing	19-38
19.7	Insulated-gate Field-effect Transistors—IGFET	19-39
19.7a	Threshold Voltage and Surface Charge Density	19-39
19.7b	Gate Capacitance	19-40
19.7c	Gain-bandwidth Product	19-41
19.7d	Effects of Substrate Potential	19-41
19.8	Accelerated Reliability Testing	19-42
19.8a	Constant-stress Testing	19-42
19.8b	Step-stress Testing	19-42
19.8c	Arrhenius Acceleration and the Log-normal Failure Distribution	19-43
19.8d	Failure Modes and Electrical-analysis Techniques	19-44
	Surface Effects on Diodes	19-44
	Surface Effects on Transistors	19-48

Section 20. Measurements of Semiconductor Parameters

Measurements at Constant Temperature

20.1	Resistivity	20-3
20.1a	Standard Resistivity Measurement	20-3
20.1b	Contactless Resistivity Measurements	20-5
	Infrared Optical Reflection	20-5
	Microwave Measurements	20-6
	Inductive Coupling	20-7
	Capacitive Coupling	20-7
20.1c	Measurements with Mechanical Contacts	20-8
	Four-point Probe	20-8
	Spreading Resistance	20-9
	Point-contact Reverse Breakdown	20-11
	Thermoelectric Power	20-12
	Rebalance Temperature	20-12
20.1d	Methods Using Alloyed or Diffused Contact	20-12
	Differential Diode Capacitance	20-12
	van der Pauw Method	20-13
20.1e	Analysis of Resistivity Measurements	20-14
20.2	Conductivity Type	20-16
20.2a	Thermoelectric Effect	20-17
20.2b	Rectification	20-18
20.3	The Hall Effect	20-18

20.3a	Measurement of the Hall Effect	20-18
20.3b	Analysis of the Hall Effect	20-20
20.4	Drift Mobility	20-22
20.5	Lifetime	20-24
20.5a	Photoconductive Decay	20-24
20.5b	Drift Length, Diffusion Length	20-25
20.5c	Photoelectromagnetic Effect	20-27
20.6	Surface Measurements	20-29
	Measurement of Surface Conductance	20-32
	Measurement of Surface Capacitance	20-33
<i>Measurements at Low Temperature</i>		
20.7	Variation of Resistivity with Temperature	20-35
20.7a	Measurement of Resistivity versus Temperature	20-41
20.7b	Magnetoresistance at Low Temperatures	20-44
20.7c	Current/Voltage Breakdown	20-44
20.8	Determination of Impurity Activation Energy and Impurity Density	20-45
Section 21. Computer-oriented Circuit Analysis and Design		
21.1	Network Topology	21-2
21.2	Nodal Analysis	21-5
21.3	The Indefinite Admittance Matrix	21-9
21.4	The Mesh Method	21-13
21.5	Loop Analysis	21-14
21.6	Cut-set Analysis	21-16
21.7	The State-variable Method	21-18
	21.7a Topological Restrictions	21-19
	21.7b Determining the Normal Tree	21-20
	21.7c Classification of the Tree and Link Elements	21-22
21.8	Transient Circuit-analysis Programs	21-33

Index follows Section 21.