

FUNDAMENTALS OF SOLID-STATE ELECTRONICS

Contents

PREFACE	vii
Chapter 1 ELECTRONS, BONDS, BANDS AND HOLES	
100 INTRODUCTION	2
110 CLASSIFICATION OF MATERIALS	4
111 Classification Schemes of Solids, 5	
* Geometrical Classification (Crystallinity vs Imperfection), 6	
* Purity Classification (Pure vs Impure), 6	
* Electrical Classification (Electrical Conductivity), 7	
* Mechanical Classification (Binding Force), 8	
120 CRYSTALLINE AND IMPURE SEMICONDUCTORS ARE NEEDED IN ELECTRON DEVICE APPLICATIONS	10
130 CRYSTAL LATTICES AND PERIODIC STRUCTURES	12
131 Description of Crystal Lattice by Vectors, 13	
* Miller Indices, 16	
132 Three-Dimensional Crystal Structures, 17	
* Diamond, Zinc Blende, Wurzite Structures, 19-22	
133 Calculation of the Atomic Density, 22	
134 Growing Single Crystals, 23	
140 WAVE MOTION OF ELECTRONS IN MATERIALS (Quantum and Wave Mechanics and Schrödinger Equation)	31
141 Dual Character of Material Particles and Electromagnetic Radiation, 32	
* The Bohr Model of Hydrogen Atom, 35	
* Applications of the Electron Energy Level and Orbit Diagrams, 41	
Emission and Absorption of Light by Hydrogen Atom, 43	
Electron in an Electric Field Around a Proton, 45	
* Summary, 46	
142 Experimental Bases for Selecting an Equation of the Matter Waves (Derivation of the Schrödinger Equation), 46	
143 Properties and Interpretations of the Wavefunction (Classical-Quantum Connections), 53	
150 SOLUTIONS OF THE SCHRODINGER EQUATION	55
* General Properties, 56	
151 Reflection of Electron at a Potential Step, 57	
152 Resonance Scattering by a Square Potential Well, 60	
153 Tunneling through a Square Potential Barrier, 62	
154 Tunneling through a Triangular Potential Barrier, 64	
155 Bound States in an Attractive Square Potential Well, 66	
156 The Hydrogen Atom, 69	
160 ELECTRON CONFIGURATIONS IN MANY-ELECTRON ATOMS	83
161 The Negatively Charged Two-Electron Hydrogen Atom, 83	
162 Many-Proton and Many-Electron Atoms, 87	

Contents

170	ELECTRONIC MODELS OF SEMICONDUCTORS AND SOLIDS	93
171	The Bond Model, 93	
172	The Band Model, 97	
173	Filling the Energy Band Levels by Electrons, 102	
180	ELEMENTARY DERIVATIONS OF THE ENERGY BAND MODELS	108
181	The Nearly Free Electron Model, 109	
182	The Tight-Binding Model, 117	
183	Energy Band Diagrams of Semiconductors, 125	
184	Energy Band of Metals and Conductors, 131	
190	COMPLETELY FILLED BAND DOES NOT CARRY A CURRENT (The Concept of Holes)	139
199	BIBLIOGRAPHY AND PROBLEMS	142

Chapter 2 HOMOGENEOUS SEMICONDUCTOR AT EQUILIBRIUM

200	INTRODUCTION	152
201	Homogeneous, 152	
202	Equilibrium, 153	
210	PURE SEMICONDUCTOR CRYSTAL	159
220	IMPURE SEMICONDUCTOR	160
221	Donors, Acceptors, Isoelectronic Traps, 161	
222	Charge States of Donors and Acceptors, 163	
223	Binding Energy of Trapped Electrons and Holes, 165	
230	ELECTRON AND HOLE CONCENTRATIONS AT THERMAL EQUILIBRIUM	169
231	The Fermi-Dirac Distribution Function, 170	
232	Electron and Hole Concentrations (Elementary Analysis), 174	
233	Electron and Hole Concentrations (Advanced Analysis), 175	
240	CALCULATIONS OF THE FERMI ENERGY LEVEL AND THE CONCENTRATION OF ELECTRONS AND HOLES	181
241	E_F , N and P in Pure Semiconductors, 181	
242	E_F , N and P in Impure or Extrinsic Semiconductors, 187	
	* The Mass Action Law, 187	
	* The Charge Neutrality Condition, 188	
	* Criterion of Extrinsic Semiconductor, 190	
	* Components of Carrier Concentration are not Additive, 191	
	* Summary of Carrier Concentration Equations, 192	
243	Temperature Dependences of N , P and E_F , 193	
244	Intrinsic Temperature, 194	
	* Quantitative Definition of T_i , 195	
	* Components of Carrier Concentration are Additive when $T > T_i$, 197	
245	Temperature Dependence of the Electron Distribution, 197	
250	DEVICE ESSENTIAL ADVANCED TOPICS	199
251	High Carrier Concentration Effects, 200	
	* Conditions of Impurity Deionization, 203	
	* Impurity Occupation Factor, 204	
	* Impurity Deionization Examples, 205	
	Deionization at High Impurity Concentration, 205	
	Deionization at Low Temperatures, 209	
253	Impurity Bands, 214	
254	Carrier Screening of Impurity, 218	
299	BIBLIOGRAPHY AND PROBLEMS	221

**Chapter 3 DRIFT, DIFFUSION, GENERATION, RECOMBINATION,
TRAPPING AND TUNNELING**

300	INTRODUCTION	232
310	DRIFT	233
311	Drift Velocity in an Electric Field, 233	
312	Drift Current, Drift Mobility and Conductivity, 238	
313	Temperature Dependences of the Drift Mobility, 239	
	* Ionized Impurity Scattering, 240	
	* Phonons for Describing Lattice Scattering, 241	
	* Lattice Scattering, 246	
314	Electric Field Dependence of Mobility, 251	
315	Intrinsic and Extrinsic Conductivities of a Semiconductor, 252	
	* Intrinsic Conductivity of Pure Semiconductor, 253	
	* Conductivity of Impure Semiconductor, 253	
320	DIFFUSION	254
321	The Einstein Relationship, 259	
322	The Boltzmann Relationship, 259	
323	Examples of Diffusion Current, 260	
330	CONSTANCY OF THE FERMI ENERGY LEVEL	261
331	The Quasi-Fermi Levels and Quasi-Fermi Potentials, 262	
340	CONTINUITY EQUATION OF CHARGE AND CURRENT	265
350	THE SHOCKLEY EQUATIONS OF SEMICONDUCTORS	268
360	GENERATION, RECOMBINATION, TRAPPING, AND TUNNELING	270
3611	Interband Thermal Generation and Recombination, 273	
3612	Interband Optical Generation and Recombination, 275	
3613	Interband Auger Recombination and Impact Generation, 278	
3621	Band-Trap Thermal (SRH) Generation-Recombination-Trapping, 281	
3622	Band-Trap Optical Generation-Recombination-Trapping, 285	
3623	Band-Trap Auger Capture and Impact Emission, 286	
363n	Three Intertrap Transitions, 286	
36n0	Elastic Tunneling, 287	
36n4	Inelastic Tunneling, 289	
36n5	Collective Transitions, 290	
370	LIFETIMES	291
371	Interband Thermal and Optical Recombination Lifetimes, 291	
372	Band-Trap Thermal (SRH) and Optical Recombination Lifetimes, 294	
373	Lifetimes for Simultaneous Presence of Many GRIT Mechanisms, 295	
380	PHYSICS AND DATA OF THE GRIT RATE COEFFICIENTS	296
381	Thermal (SRH) Capture and Emission Rates, 296	
382	Optical Emission Rate, 300	
383	Interband Optical Generation Rate, 300	
384	Interband Impact Generation Rate, 302	
385	Interband Tunneling Rate, 303	
386	Band-Trap Tunneling, 305	
399	BIBLIOGRAPHY AND PROBLEMS	306

Chapter 4 METAL-OXIDE-SEMICONDUCTOR CAPACITOR (MOSC)

400	INTRODUCTION	312
401	Fabrication of an Silicon VLSI MOSC, 314	
402	Ideal C-V Curves, 320	
403	Real C-V Curves, 323	
410	CHARGE CONTROL MODEL OF MOSC	325
411	Charge Control C-V Theory without Energy Band Diagram, 336	
	* Depletion Capacitance, 338	
	* High-Frequency Capacitance, 339	
	* Low-Frequency Capacitance, 342	
	* Accumulation Capacitance, 344	
	* Flat-Band Capacitance, 344	
	* Summary, 346	
412	Advanced Charge-Control C-V Theory, 347	
	* Relating Electric Field to Potential at Semiconductor Surface, 347	
	* Relating Surface Potential to Gate Voltage, 349	
	* The Exact Low-Frequency MOS Capacitance, 353	
	* Depletion and High-Frequency Capacitances, 353	
413	Energy Band Diagram of MOSC, 354	
420	TRANSIENTS IN MOSC	363
421	Capacitance Transients, 365	
422	Current Transients, 369	
430	EXACT SMALL-SIGNAL EQUIVALENT CIRCUIT OF MOSC	374
499	BIBLIOGRAPHY AND PROBLEMS	375

Chapter 5 P/N AND OTHER JUNCTION DIODES

500	INTRODUCTION	382
510	FABRICATION OF A DIFFUSED P/N JUNCTION DIODE	385
511	Diffusion and Fisk's Law, 385	
512	Physics and Data of the Diffusivity, 389	
513	Diffused Junction Depth Calculation, 395	
520	EQUILIBRIUM ELECTRICAL PROPERTIES OF A P/N JUNCTION	397
521	Equilibrium Energy Band Diagram, 399	
	* Position of the Fermi Level, 399	
	* Intrinsic Fermi Level and Electric Potential, 403	
522	Equilibrium Potential Barrier Height in a p/n Junction, 404	
523	Equilibrium Potential Variation in a p/n Junction, 408	
524	Application of the Gauss Theorem to a p/n Junction, 416	
525	Comparing the Depletion Approximation with the Exact Solution, 418	
530	DC ELECTRICAL CHARACTERISTICS OF A P/N JUNCTION	420
531	Energy Band Diagram of a Biased p/n Junction, 424	
	* Reverse bias, 424	
	* Forward bias, 427	
532	The Shockley Diode Equation, 430	
533	Physics of the Shockley Diode Equation, 432	
534	Numerical Example of a Shockley Diode, 436	
535	The Sah-Noyce-Shockley Diode Equation, 436	

536	Breakdown of Reverse DC Current in a p/n Junction, 441	
	* Mathematical Formulation, 443	
	* Basic Physics of the Parameters, 446	
	* Simple Solution, 448	
537	Experimental-Theoretical Comparison, 451	
540	SMALL-SIGNAL CHARACTERISTICS OF A P/N JUNCTION	455
541	Small-Signal Charge-Control Circuit Elements, 456	
542	Small-Signal Numerical Examples of a Si p/n Junction, 458	
550	SWITCHING TRANSIENTS IN A P/N JUNCTION	461
551	Charge-Control Switching Analysis of a p/n Junction, 462	
552	Turn-On Transient in a p/n Junction, 464	
553	Turn-Off Transient in a p/n Junction, 467	
554	Capacitance and Current Trapping Transients in a p/n Junction, 470	
560	METAL/SEMICONDUCTOR DIODE	474
561	Equilibrium Energy Band Diagrams of the Schottky Barrier, 478	
562	DC Current-Voltage Characteristics of the M/S Diode	
	- Bethe Theory, 483	
563	Experimental M/S Diodes, 489	
564	Effect of Semiconductor Voltage Drop - Mott Theory, 493	
565	Integrated Circuit Schottky Barrier Diode Layouts, 497	
570	TUNNEL DIODES	499
580	LIMITING MECHANISMS OF DC TERMINAL CURRENT OF DIODES	500
581	Current Limits in Metal/Semiconductor Diodes, 500	
582	Current Limits in p/n Junction Diodes, 502	
583	Contact Resistance, 506	
590	SEMICONDUCTOR/SEMICONDUCTOR HETEROJUNCTION DIODES	510
591	Energy Band Diagrams of s/s Heterojunctions, 510	
	* Trapless s/s Interface, 510	
	* Trappy s/s Interface, 512	
592	Electrical Characteristics of s/s Heterojunctions, 513	
599	BIBLIOGRAPHY AND PROBLEMS	514

Chapter 6 METAL-OXIDE-SEMICONDUCTOR AND OTHER FIELD-EFFECT TRANSISTORS

600	INTRODUCTION	524
610	PHYSICAL STRUCTURE OF THE INVERSION-CHANNEL MOSFET	526
	* Coordinate System, 526	
	* Body of the Semiconductor, 527	
	* Source and Drain, 527	
	* Gate Oxide, Gate Contact, Gate Width, 527	
	* Channel Type, Channel Length, Channel Thickness, 528	
	* Field Oxide, Pad Oxide, 528	
620	QUALITATIVE DESCRIPTION OF DC MOSFET CHARACTERISTICS	529
621	Physics of MOST Channel Current, 529	
622	Output and Transfer D.C. Characteristics, 529	
623	Four Basic MOST Current-Voltage Characteristics, 530	
630	TYPICAL FABRICATION STEPS OF AN N-CHANNEL MOSFET	533
	* Description of the Fabrication Steps, 535	

640	D.C. CHARACTERISTICS OF MOSFET (Elementary Analysis)	538
641	Conductivity Modulation Model of the MOSFET (D.C. Drift Current and Charge Control Analysis), 541	
	* Current-Charge Equation from Longitudinal Electric Field, 542	
	* Voltage-Current Equation from Transverse Electric Field, 545	
642	Oxide and Interface Trapped Charges, (Instability, Aging, Failure), 547	
643	The MOSFET Equations and D.C. Characteristics, 550	
644	Numerical Examples of MOSFET D.C. Characteristics, 558	
650	SMALL-SIGNAL EQUIVALENT CIRCUIT MODEL OF MOSFET	559
651	Charge-Control Analysis of Capacitance Elements, 560	
	* Asymptotic Results at Low Drain Voltage and Current Saturation, 565	
652	High-Frequency Response of MOS Transistor, 568	
	* Transconductance Cutoff Frequency, 568	
	* Gain-Bandwidth Product, 570	
653	Numerical Example of Small-Signal Characteristics, 571	
654	Distributed Low-Frequency Small-Signal Model, 572	
660	SWITCHING PROPERTIES OF MOSFET	576
661	Intrinsic Delay, 577	
662	Power-Delay Product (Figure of Merit), 581	
663	Charging and Discharging a Capacitor - Extrinsic Delays, 583	
	* Fundamental MOSFET Switching Equation, 586	
	* Charging a Capacitor, 588	
	* Discharging a Capacitor, 590	
	* Charging-Discharging Comparison, 592	
	* Charging-Discharging Cycle Time, 592	
	* Charge Transferring Between Two Capacitors, 592	
670	CIRCUIT APPLICATIONS OF MOSFET	596
	* MOST Circuit Symbols - Evolution Chronology, 596	
	* Current-Voltage Equations for MOS Circuit Analysis, 601	
671	Dynamic Random Access Memory Cell, the DRAM, 603	
	* Definition of Memory Terms, 603	
	* Brief Manufacturing History of DRAM Chip, 605	
	* Equivalent Circuit Model of a DRAM Cell, 608	
	* Cell Array Architecture of a DRAM Chip, 608	
	* Basic Operation Principle of DRAM Cell, 610	
	Write 1 Operation - Bit Bunching, Line Driver, Precharge, 611	
	Read 1 Operation - Destructive Readout, Self-Restore/Force-Read, Dummy Cell, 611	
	Refresh Cycle and Origin of 'Dynamic', 612	
672	The MOS Inverter Circuits, 614	
	* Encyclopedia of Twenty MOS Inverter Circuits, 614	
	* Analysis of the Three NMOS Inverter Circuits, 620	
	The RENMOS Inverter, 621	
	The DENMOS Inverter, 622	
	The EENMOS Inverter, 623	
	Power Dissipation of the Three NMOS Inverters, 623	
	* The CMOS Inverter Circuit, 624	
	Why CMOS?, 624	
	Evolution History of CMOS Structures, 625	
	D.C. Analysis of the CMOS Inverter Circuit, 629	

Contents

673	Static Random Access Memory Cell (SRAM)	632	
674	Nonvolatile Random Access MOS Memories (ROM, PROM's)	636	
	* Read Only Memory (ROM)	636	
	* Programmable Read Only Memory (PROM)	637	
	* Erasable Programmable Read Only Memories (EPROMs)	637	
	UV-EPROM (1971-1991!),	639	
	Flash-EPROM (a EEPROM),	640	
	F-EPROMs (FMOS and FRAM),	641	
680	BEYOND THE CONDUCTIVITY MODULATION MODEL		644
681	Effect of bulk charge (Body Effects: Dopant and Substrate Bias)	645	
	* Origin of the Bulk Charge,	645	
	* Analytical Approximation of Bulk Charge (Depletion Model),	647	
	* Body Effects on Threshold Voltage,	649	
	* Body Effects on I-V Shape,	650	
	* Five Illustrations and a Numerical Example of the Body Effect,	651	
682	Subthreshold Characteristics (Diffusion Current)	653	
	* Definition of the Subthreshold Range,	656	
	* Intrinsic Surface - Onset of Drift Current,	656	
	* Analysis of the Subthreshold Current,	657	
	* Subthreshold Drain Current Equation,	660	
	* Dependence of Subthreshold Current on Drain Voltage,	660	
	* Dependence of Subthreshold Current on Gate Voltage,	660	
	* Temperature Dependence of the Subthreshold Current,	661	
683	Effects of Oxide and Interface Traps	662	
	* Oxide Traps,	662	
	* Interface Traps,	665	
684	High Electric Field and High Voltage Effects	667	
	* I-V with Electric Field Dependent Mobility,	668	
	Longitudinal Field Dependent Mobility Effects,	669	
	Transverse Field Dependent Mobility Effects,	670	
	* Electric Field and Voltage Dependent Generation-Recombination-Trapping,	674	
	Five Trap Charging-Discharging Processes via Capture and Emission,	675	
	Ten Trap Charging-Discharging Processes via Elastic Tunneling,	676	
	Eight Trap Generation-Annihilation Processes via Hydrogenation,	676	
	Hydrogenation of Boron and Group-III Acceptors in Si,	677	
685	Short Channel and Narrow Gate Effects	679	
	* Three Short Channel Effects and Lowly Doped Drain,	679	
	* Three Narrow Gate Effects,	683	
690	OTHER FIELD-EFFECT TRANSISTORS - EVOLUTION HISTORY		687
	* MESFETs,	687	
	* MOSFETs,	687	
	* The First JGFET (Surface-Ion Induced Inversion Channel),	689	
	* JGFET,	690	
	* Two Current Saturation Mechanisms (Channel Pinch-off and Carrier Depletion),	690	
	* High-Mobility Confined-Channel Heterojunction FETs,	691	
699	BIBLIOGRAPHY AND PROBLEMS		694

**Chapter 7 BIPOLAR JUNCTION TRANSISTOR AND OTHER
BIPOLAR TRANSISTOR DEVICES**

700	INTRODUCTION	704
710	BACKGROUND AND HISTORY	704
720	FABRICATION OF A DOUBLE DIFFUSED SILICON BJT	709
730	D.C. CHARACTERISTICS OF IDEAL AND REAL BJT'S	712
731	Two-Diode D.C. Circuit Representation of BJT, 712	
732	Data of BJT Characteristics, 718	
733	Derivation of the D.C. Characteristics of p/n/p BJT, 723	
	* The Shockley BJT Equations, 730	
	* The SNS BJT Equations, 731	
734	The Original and Extended Ebers-Moll Equations of BJT, 733	
735	Two-Port Nonlinear D.C. Network Representations of BJT, 739	
	* General Common-Base Two-port Network Equations, 740	
	* General Common-Emitter Two-port Network Equations, 742	
	* Circuit Models in the Four Operation Modes, 743	
	Forward Active Mode, 743	
	Reverse Active Mode, 748	
	Cutoff Mode, 748	
	Saturation Mode, 749	
736	Lumped D.C. Models of Realistic Multi-Dimensional BJT, 754	
	* Non-overlap Collector Diode, 754	
	* Base Spreading Resistance, 754	
737	Material and Structural Dependences of D.C. Two-Port Parameters of BJT, 758	
	* Diffusion-Drift Transport Time in the Quasi-Neutral Base Layer, 759	
	* Gummel Number in the Quasi-Neutral Base Layer, 759	
	* Gummel Number in the Quasi-Neutral Emitter Layer, 763	
	* Emitter Injection Efficiency Calculated from the Gummel Numbers, 764	
738	Bias Dependences of the D.C. Parameters of BJT, 765	
	* The Early Effects in BJT and Lowly-Doped Collector, 765	
	* The SNS Effects in BJT (α and β Fall-Off at Low Current), 770	
	* Alpha and Beta Fall-Off at High Current in BJT, 774	
	* The Kirk effects in BJT, 780	
739	Collector Multiplication and Negative Resistance, 783	
	* Numerical Example, 788	
740	SMALL-SIGNAL CHARACTERISTICS OF BJT	791
	* The Small-Signal Condition, 791	
	* Comparing the Charge-Control and Exact Small-Signal Analyses, 793	
	Exact Analysis for Small-Signal Equivalent Circuit Models, 793	
	Charge-Control Analysis for Small-Signal Equivalent Circuit Models, 796	
741	Common-Base Small-Signal Tee (CBss-Tee) Models of BJT, 797	
	* Low-Frequency CBss-Tee Model of Intrinsic BJT, 799	
	* High-Frequency CBss-Tee Model of Intrinsic BJT, 804	
	* CBss-Tee Equivalent Circuit Model of Real BJT, 811	
742	Maximum Frequency of Oscillation of BJT, 814	
	* The Gibbons Frequency, 814	
743	Common-Emitter Small-Signal Hybrid-Pi (CEss-H π) Model of BJT, 817	
	* The Conductance Elements of the CEss-H π BJT Model, 819	
	* Summary of BJT CEss-H π Conductance Elements and Numerical Example, 822	
	* Intrinsic Charge Control Capacitances of CEss-H π BJT Model, 823	
	* Parasitics of the CEss-H π BJT Model, 823	
744	Common-Emitter Current Gain, Cutoff Frequency and Bandwidth, 823	

750	LARGE-SIGNAL SWITCHING CHARACTERISTICS OF BJT	829
751	The Diffusion and Charge-Control Equations, 830	
	* Charge-Control Equations of a General Slab, 832	
	* Charge-Control Equations of the Entire BJT, 832	
	* Charge-Control Equations of the Quasi-Neutral Base Layer, 832	
	* Charge-Control Equations of the Space-Charge Layers, 833	
	Emitter-Base Space-Charge Layer, 834	
	Collector-Base Space-Charge Layer, 834	
	* Complete Base-Charge-Control Equations, 834	
	* The Base Transport Time Parameters, t_{BF} and t_{BR} , 836	
	* Relating the Charge-Control and Ebers-Moll Parameters, 837	
752	Common-Base Large-Signal BJT Switching Transients, 838	
	* Common-Base Turn-On Transients in BJT, 840	
	Phase I CB Turn-On Transient - Charge-Control Solution, 843	
	Phase II (including Phase I) CB Turn-On Transient - Lump Model, 848	
	Phase II CB Turn-On Transient - Exact Solutions, 851	
	Phase II CB Turn-On Transient - Effects of Parasitics, 854	
	* Common-Base Turn-Off Transients in BJT, 856	
	Charge-Control Solutions of CB Turn-Off Transients, 857	
	Exact Solutions of CB Turn-Off Transients, 860	
753	Common-Emitter Large-Signal BJT Switching Transients, 862	
	* Common-Emitter Turn-On Transient, 862	
	* Capacitance Speed-up of Common-Emitter Turn-On Transient, 865	
	* Common-Emitter Turn-Off Transient, 866	
754	Comparison of CB and CE BJT Switching Transients, 867	
	* Short-Circuit or Voltage Source in CB or CE Configuration (S,CE,CB), 867	
	* Open-Circuit or Current Source in CB Configuration (O,CB), 867	
	* Open-Circuit or Current Source in CE Configuration (O,CE), 867	
755	Speeding Up the BJT via Technology, 869	
	* Technology of Reducing Recombination Lifetime τ_B , 872	
	* Speeding-Up via Geometry and Resistivity Reduction, 876	
	* Performance Comparison of Four Micron-Submicron BJTs, 878	
756	Propagation Delay in Ring Oscillator, 882	
760	CIRCUIT APPLICATIONS OF BIPOLAR JUNCTION TRANSISTOR	885
761	The BJT Digital Inverters, 885	
762	The Common-Emitter BJT Inverter, 887	
	* Charging Up the Emitter-Base Space-Charge Layer Capacitance, 888	
	* Charging Up the Quasi-Neutral Base in the Active Range, 889	
	* Further Charging Up the Quasi-Neutral Base in the Saturation Range, 890	
	* Discharging the Stored Base Charge in the Saturation Range, 892	
	* Discharging the Stored Base Charge in the Active Region, 895	
	* Discharging the Space-Charge Layer Capacitances, 895	
	* Average Propagation Delay in CE BJT Inverter, 896	
763	Speeding Up the CE BJT Inverter, 897	
	* Large Turn-On and Turn-Off Overdrives, 897	
	* Input Speed-Up Capacitor, 897	
	* Schottky-Barrier Bethe Diode Clamp, 897	
764	The Emitter-Coupled 2-BJT Inverter (ECL), 899	
765	The CB-CE Transistor-Transistor Coupled 2-BJT Inverter (TTL), 902	

766	The Bipolar-MOS Inverters (BiMOS, BiCMOS, CBiCMOS), 906	
	* Shunt-BiMOS: Emitter-Base Junction Shunted by MOST, 909	
	Collector Follower, 911	
	Emitter Inverter, 912	
	* Series-BiMOS: MOST in Series with Base Terminal, 915	
	* BiCMOS and CBiCMOS Inverters, 917	
	* The Optimum 6-Transistor CBiCMOS Inverter, 928	
770	THE HETEROSTRUCTURE BIPOLAR JUNCTION TRANSISTORS	
	(HBJTs or HBTs)	931
771	Historical Background, 931	
772	Fabrication Methods of $\text{Ge}_x\text{Si}_{1-x}$ HBJT, 936	
773	Operation Principle of HBJTs, 937	
774	Energy Bands and Phonon Spectra of Commensurate Layers, 945	
780	THE FOUR-LAYER PNPN DEVICES	955
	* Shockley's "Hook" Collector Theory, 960	
	* Shockley's Four-Layer Diode Venture, 961	
	* Silicon Controlled Rectifier (SCR), 962	
	* Shorted-Emitter or Shunted-Emitter SCR, 964	
	* Junction-Gate SCR, 965	
	* Remote-Gate SCR, 965	
	* Bilateral SCR, 965	
781	Four-Layer PNP Diode Characteristics, 965	
	* D.C. Voltage-Current Characteristics of 4-Layer Diode, 966	
	* Physics of the 4-Layer Diode V-I Characteristics, 970	
	* Switching Transient in 4-Layer Diode, 972	
782	PNPN Triode (SCR) Characteristics, 974	
	* Basic SCR, 975	
	* Shorted-Emitter or Shunted-Emitter SCR, 977	
	* Junction-Gate SCR, 978	
	* Remote-Gate SCR, 978	
	* Bilateral SCR, 978	
783	MOS-SCR, 979	
784	Latch-up in CMOS, 980	
799	BIBLIOGRAPHY AND PROBLEMS	981
	APPENDIX A NOTATION CONVENTION	992
	INDEX	997