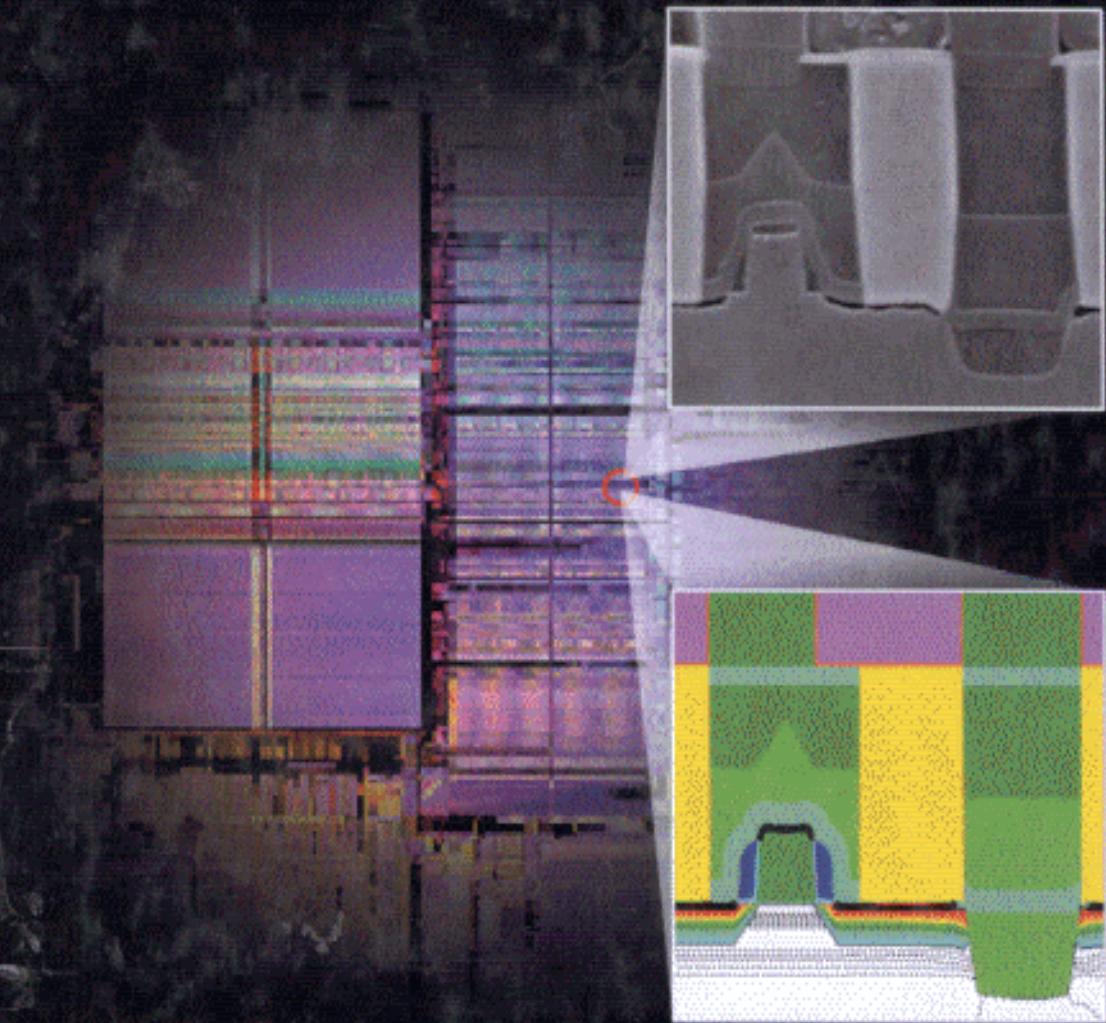


SILICON VLSI TECHNOLOGY

Fundamentals, Practice and Modeling



James D. Plummer • Michael D. Deal • Peter B. Griffin

Prentice Hall Electronics and VLSI Series—Charles Sodini, Series Editor

Contents

Preface	xi
---------------	----

Chapter 1	Introduction and Historical Perspective	1
1.1	Introduction	1
1.2	Integrated Circuits and the Planar Process—Key Inventions That Made It All Possible	7
1.3	Semiconductors	13
1.4	Semiconductor Devices	33
1.4.1	PN Diodes	33
1.4.2	MOS Transistors	36
1.4.3	Bipolar Junction Transistors	39
1.5	Semiconductor Technology Families	41
1.6	Modern Scientific Discovery—Experiments, Theory, and Computer Simulation	43
1.7	The Plan For This Book	45
1.8	Summary of Key Ideas	46
1.9	References	46
1.10	Problems	47
Chapter 2	Modern CMOS Technology	49
2.1	Introduction	49
2.2	CMOS Process Flow	50
2.2.1	The Beginning—Choosing a Substrate	51
2.2.2	Active Region Formation	52
2.2.3	Process Option for Device Isolation—Shallow Trench Isolation	57
2.2.4	N and P Well Formation	60
2.2.5	Process Options for Active Region and Well Formation	63
2.2.6	Gate Formation	71
2.2.7	Ti _x or Extension (LDD) Formation	76
2.2.8	Source/Drain Formation	80
2.2.9	Contact and Local Interconnect Formation	82
2.2.10	Multilevel Metal Formation	84
2.3	Summary of Key Ideas	90
2.4	Problems	91

Chapter 3	Crystal Growth, Wafer Fabrication and Basic Properties of Silicon Wafers	93
3.1	Introduction	93
3.2	Historical Development and Basic Concepts	93
3.2.1	Crystal Structure	94
3.2.2	Defects in Crystals	97
3.2.3	Raw Materials and Purification	101
3.2.4	Czochralski and Float-Zone Crystal Growth Methods	102
3.2.5	Wafer Preparation and Specification	105
3.3	Manufacturing Methods and Equipment	109
3.4	Measurement Methods	111
3.4.1	Electrical Measurements	111
3.4.1.1	Hot Point Probe	112
3.4.1.2	Sheet Resistance	113
3.4.1.3	Hall Effect Measurements	115
3.4.2	Physical Measurements	117
3.4.2.1	Defect Etches	117
3.4.2.2	Fourier Transform Infrared Spectroscopy (FTIR)	118
3.4.2.3	Electron Microscopy	119
3.5	Models and Simulation	121
3.5.1	Czochralski Crystal Growth	122
3.5.2	Dopant Incorporation during CZ Crystal Growth	125
3.5.3	Zone Refining and FZ Growth	128
3.5.4	Point Defects	131
3.5.5	Oxygen in Silicon	138
3.5.6	Carbon in Silicon	142
3.5.7	Simulation	143
3.6	Limits and Future Trends in Technologies and Models	144
3.7	Summary of Key Ideas	146
3.8	References	147
3.9	Problems	148
Chapter 4	Semiconductor Manufacturing—Clean Rooms, Wafer Cleaning, and Gettering	151
4.1	Introduction	151
4.2	Historical Development and Basic Concepts	154
4.2.1	Level 1 Contamination Reduction: Clean Factories	157
4.2.2	Level 2 Contamination Reduction: Wafer Cleaning	159
4.2.3	Level 3 Contamination Reduction: Gettering	161
4.3	Manufacturing Methods and Equipment	165
4.3.1	Level 1 Contamination Reduction: Clean Factories	165
4.3.2	Level 2 Contamination Reduction: Wafer Cleaning	166
4.3.3	Level 3 Contamination Reduction: Gettering	167
4.4	Measurement Methods	169
4.4.1	Level 1 Contamination Reduction: Clean Factories	169

4.4.2	Level 2 Contamination Reduction: Wafer Cleaning.....	173
4.4.3	Level 3 Contamination Reduction: Gettering.....	176
4.5	Models and Simulation.....	180
4.5.1	Level 1 Contamination Reduction: Clean Factories.....	181
4.5.2	Level 2 Contamination Reduction: Wafer Cleaning.....	184
4.5.3	Level 3 Contamination Reduction: Gettering.....	186
	4.5.3.1 Step 1: Making the Metal Atoms Mobile	186
	4.5.3.2 Step 2: Metal Diffusion to the Gettering Site.....	187
	4.5.3.3 Step 3: Trapping the Metal Atoms at the Gettering Site.....	190
4.6	Limits and Future Trends in Technologies and Models	193
4.7	Summary of Key Ideas	196
4.7	References	196
4.9	Problems	198

Chapter 5**Lithography** 201

5.1	Introduction.....	201
5.2	Historical Development and Basic Concepts	203
5.2.1	Light Sources.....	206
5.2.2	Wafer Exposure Systems.....	208
	5.2.2.1 Optics Basics—Ray Tracing and Diffraction	209
	5.2.2.2 Projection Systems (Fraunhofer Diffraction).....	212
	5.2.2.3 Contact and Proximity Systems (Fresnel Diffraction)	219
5.2.3	Photoresists	221
	5.2.3.1 g-line and i-line Resists	223
	5.2.3.2 Deep Ultraviolet (DUV) Resists.....	225
	5.2.3.3 Basic Properties and Characterization of Resists	227
5.2.4	Mask Engineering—Optical Proximity Correction and Phase Shifting	230
5.3	Manufacturing Methods and Equipment.....	234
5.3.1	Wafer Exposure Systems	234
5.3.2	Photoresists	238
5.4	Measurement Methods.....	241
5.4.1	Measurement of Mask Features and Defects	242
5.4.2	Measurement of Resist Patterns.....	244
5.4.3	Measurement of Etched Features.....	244
5.5	Models and Simulation.....	246
5.5.1	Wafer Exposure Systems	247
5.5.2	Optical Intensity Pattern in the Photoresist	253
5.5.3	Photoresist Exposure	259
	5.5.3.1 g-line and i-line DNQ Resists.....	259
	5.5.3.2 DUV Resists.....	263
5.5.4	Postexposure Bake (PEB).....	264
	5.5.4.1 g-line and i-line DNQ Resists.....	264
	5.5.4.2 DUV Resists.....	266
5.5.5	Photoresist Developing	267
5.5.6	Photoresist Postbake	270

5.6	5.5.7 Advanced Mask Engineering	271
	Limits and Future Trends in Technologies and Models	272
5.6.1	Electron Beam Lithography	273
5.6.2	X-ray Lithography	275
5.6.3	Advanced Mask Engineering	277
5.6.4	New Resists	278
5.7	Summary of Key Ideas	281
5.8	References	281
5.9	Problems	283
Chapter 6	Thermal Oxidation and the Si/SiO₂ Interface	287
6.1	Introduction	287
6.2	Historical Development and Basic Concepts	290
6.3	Manufacturing Methods and Equipment	296
6.4	Measurement Methods	298
6.4.1	Physical Measurements	299
6.4.2	Optical Measurements	299
6.4.3	Electrical Measurements—The MOS Capacitor	301
6.5	Models and Simulation	312
6.5.1	First-Order Planar Growth Kinetic —The Linear Parabolic Model	313
6.5.2	Other Models for Planar Oxidation Kinetics	322
6.5.3	Thin Oxide SiO ₂ Growth Kinetics	326
6.5.4	Dependence of Growth Kinetics on Pressure	328
6.5.5	Dependence of Growth Kinetics on Crystal Orientation	329
6.5.6	Mixed Ambient Growth Kinetics	332
6.5.7	2D SiO ₂ Growth Kinetics	333
6.5.8	Advanced Point Defect Based Models for Oxidation	339
6.5.9	Substrate Doping Effects	343
6.5.10	Polysilicon Oxidation	345
6.5.11	Si ₃ N ₄ Growth and Oxidation Kinetics	347
6.5.12	Silicide Oxidation	350
6.5.13	Si/SiO ₂ Interface Charges	352
6.5.14	Complete Oxidation Module Simulation	357
6.6	Limits and Future Trends in Technologies and Models	359
6.7	Summary of Key Ideas	361
6.8	References	361
6.9	Problems	364
Chapter 7	Dopant Diffusion	371
7.1	Introduction	371
7.2	Historical Development and Basic Concepts	374
7.2.1	Dopant Solid Solubility	375
7.2.2	Diffusion from a Macroscopic Viewpoint	377
7.2.3	Analytic Solutions of the Diffusion Equation	379
7.2.4	Gaussian Solution in an Infinite Medium	380

7.2.5	Gaussian Solution Near a Surface	381
7.2.6	Error-Function Solution in an Infinite Medium	382
7.2.7	Error-Function Solution Near a Surface	384
7.2.8	Intrinsic Diffusion Coefficients of Dopants in Silicon	386
7.2.9	Effect of Successive Diffusion Steps	388
7.2.10	Design and Evaluation of Diffused Layers	389
7.2.11	Summary of Basic Diffusion Concepts	392
7.3	Manufacturing Methods and Equipment	392
7.4	Measurement Methods	395
7.4.1	SIMS	396
7.4.2	Spreading Resistance	397
7.4.3	Sheet Resistance	398
7.4.4	Capacitance Voltage	399
7.4.5	TEM Cross Section	399
7.4.6	2D Electrical Measurements Using Scanning Probe Microscopy	400
7.4.7	Inverse Electrical Measurements	402
7.5	Models and Simulation	403
7.5.1	Numerical Solutions of the Diffusion Equation	403
7.5.2	Modifications to Fick's Laws to Account for Electric Field Effects	406
7.5.3	Modifications to Fick's Laws to Account for Concentration-Dependent Diffusion	409
7.5.4	Segregation	413
7.5.5	Interfacial Dopant Pileup	415
7.5.6	Summary of the Macroscopic Diffusion Approach	417
7.5.7	The Physical Basis for Diffusion at an Atomic Scale	417
7.5.8	Oxidation-Enhanced or -Retarded Diffusion	419
7.5.9	Dopant Diffusion Occurs by Both I and V	422
7.5.10	Activation Energy for Self-Diffusion and Dopant Diffusion	426
7.5.11	Dopant-Defect Interactions	426
7.5.12	Chemical Equilibrium Formulation for Dopant-Defect Interactions	432
7.5.13	Simplified Expression for Modeling	434
7.5.14	Charge State Effects	436
7.6	Limits and Future Trends in Technologies and Models	439
7.6.1	Doping Methods	440
7.6.2	Advanced Dopant Profile Modeling—Fully Kinetic Description of Dopant-Defect Interactions	440
7.7	Summary of Key Ideas	442
7.8	References	443
7.9	Problems	445

Chapter 8	Ion Implantation	451
8.1	Introduction	451
8.2	Historical Development and Basic Concepts	451
8.2.1	Implants in Real Silicon—The Role of the Crystal Structure	461
8.3	Manufacturing Methods and Equipment	463

8.3.1	High-Energy Implants	466
8.3.2	Ultralow Energy Implants	468
8.3.3	Ion Beam Heating	469
8.4	Measurement Methods	469
8.5	Models and Simulations	470
8.5.1	Nuclear Stopping	471
8.5.2	Nonlocal Electronic Stopping	473
8.5.3	Local Electronic Stopping	474
8.5.4	Total Stopping Powers	475
8.5.5	Damage Production	476
8.5.6	Damage Annealing	479
8.5.7	Solid-Phase Epitaxy	482
8.5.8	Dopant Activation	484
8.5.9	Transient-Enhanced Diffusion	486
8.5.10	Atomic-Level Understanding of TED	488
8.5.11	Effects on Devices	497
8.6	Limits and Future Trends in Technologies and Models	499
8.7	Summary of Key Ideas	500
8.8	References	500
8.9	Problems	502

Chapter 9 Thin Film Deposition 509

9.1	Introduction	509
9.2	Historical Development and Basic Concepts	511
9.2.1	Chemical Vapor Deposition (CVD)	512
9.2.1.1	Atmospheric Pressure Chemical Vapor Deposition (APCVD)	513
9.2.1.2	Low-Pressure Chemical Vapor Deposition (LPCVD)	525
9.2.1.3	Plasma-Enhanced Chemical Vapor Deposition (PECVD)	527
9.2.1.4	High-Density Plasma Chemical Vapor Deposition (HDPCVD)	530
9.2.2	Physical Vapor Deposition (PVD)	530
9.2.2.1	Evaporation	531
9.2.2.2	Sputter Deposition	539
9.3	Manufacturing Methods	554
9.3.1	Epitaxial Silicon Deposition	556
9.3.2	Polycrystalline Silicon Deposition	558
9.3.3	Silicon Nitride Deposition	561
9.3.4	Silicon Dioxide Deposition	563
9.3.5	Al Deposition	565
9.3.6	Ti and Ti-W Deposition	566
9.3.7	W Deposition	567
9.3.8	TiSi ₂ and WSi ₂ Deposition	567
9.3.9	TiN Deposition	568
9.3.10	Cu Deposition	570
9.4	Measurement Methods	572

9.5	Models and Simulation.....	573
9.5.1	Models for Deposition Simulations	573
9.5.1.1	Models in Physically Based Simulators Such as SPEEDIE	574
9.5.1.2	Models for Different Types of Deposition Systems.....	582
9.5.1.3	Comparing CVD and PVD and Typical Parameter Values	587
9.5.2	Simulations of Deposition Using a Physically Based Simulator, SPEEDIE	590
9.5.3	Other Deposition Simulations	598
9.6	Limits and Future Trends in Technologies and Models	601
9.7	Summary of Key Ideas	602
9.8	References	603
9.9	Problems	605

Chapter 10 Etching 609

10.1	Introduction.....	609
10.2	Historical Development and Basic Concepts	612
10.2.1	Wet Etching	612
10.2.2	Plasma Etching	619
10.2.2.1	Plasma Etching Mechanisms	621
10.2.2.2	Types of Plasma Etch Systems	628
10.2.2.3	Summary of Plasma Systems and Mechanisms	636
10.3	Manufacturing Methods.....	637
10.3.1	Plasma Etching Conditions and Issues	638
10.3.2	Plasma Etch Methods for Various Films	643
10.3.2.1	Plasma Etching Silicon Dioxide	644
10.3.2.2	Plasma Etching Polysilicon	647
10.3.2.3	Plasma Etching Aluminum	649
10.4	Measurement Methods.....	650
10.5	Models and Simulation.....	653
10.5.1	Models for Etching Simulation	653
10.5.2	Etching Models—Linear Etch Model	656
10.5.3	Etching Models—Saturation/Adsorption Model for Ion-Enhanced Etching	663
10.5.4	Etching Models—More Advanced Models	669
10.5.5	Other Etching Simulations	671
10.6	Limits and Future Trends in Technologies and Models	675
10.7	Summary of Key Ideas	676
10.8	References	677
10.9	Problems	679

Chapter 11 Back-End Technology 681

11.1	Introduction.....	681
11.2	Historical Development and Basic Concepts	687
11.2.1	Contacts	688
11.2.2	Interconnects and Vias	695

11.2.3 Dielectrics	707
11.3 Manufacturing Methods and Equipment	715
11.3.1 Silicided Gates and Source/Drain Regions	716
11.3.2 First-level Dielectric Processing	718
11.3.3 Contact Formation	719
11.3.4 Global Interconnects	721
11.3.5 IMD Deposition and Planarization	723
11.3.6 Via Formation	724
11.3.7 Final Steps	725
11.4 Measurement Methods	725
11.4.1 Morphological Measurements	726
11.4.2 Electrical Measurements	726
11.4.3 Chemical and Structural Measurements	732
11.4.4 Mechanical Measurements	734
11.5 Models and Simulation	737
11.5.1 Silicide Formation	738
11.5.2 Chemical-Mechanical Polishing	744
11.5.3 Reflow	746
11.5.4 Grain Growth	753
11.5.5 Diffusion in Polycrystalline Materials	762
11.5.6 Electromigration	765
11.6 Limits and Future Trends in Technologies and Models	776
11.7 Summary of Key Ideas	780
11.8 References	781
11.9 Problems	784
Appendices	787
A.1 Standard Prefixes	787
A.2 Useful Conversions	787
A.3 Physical Constants	788
A.4 Physical Properties of Silicon	788
A.5 Properties of Insulators Used in Silicon Technology	789
A.6 Color Chart for Deposited Si_3N_4 Films Observed Perpendicularly under Daylight Fluorescent Lighting	789
A.7 Color Chart for Thermally Grown SiO_2 Films Observed Perpendicularly under Daylight Fluorescent Lighting	790
A.8 Irwin Curves	791
A.9 Error Function	793
A.10 List of Important Symbols	797
A.11 List of Common Acronyms	798
A.12 Tables in Text	801
A.13 Answers to Selected Problems	802
Index	805