
Contents

1	INTRODUCTION	1
1.1	RISE OF LAYOUT CONTEXT DEPENDENCE	2
1.2	VARIABILITY AND UNCERTAINTY	3
1.3	CHARACTERIZATION VS. MODELING	5
1.4	MODEL TO HARDWARE MATCHING	6
1.5	DESIGN FOR MANUFACTURABILITY VS. STATISTICAL DESIGN	6

Part I Sources of Variability

2	FRONT END VARIABILITY	11
2.1	INTRODUCTION	11
2.2	VARIABILITY OF GATE LENGTH	15
2.2.1	Gate Length Variability: Overview	15
2.2.2	Contributions of Photolithography	17
2.2.3	Impact of Etch	22
2.2.4	Line Edge Roughness	22
2.2.5	Models of L_{gate} Spatial Correlation	24
2.3	GATE WIDTH VARIABILITY	26
2.4	THRESHOLD VOLTAGE VARIABILITY	27
2.5	THIN FILM THICKNESS	32
2.6	LATTICE STRESS	35
2.7	VARIABILITY IN EMERGING DEVICES	36
2.8	PHYSICAL VARIATIONS DUE TO AGING AND WEAROUT	39
2.9	SUMMARY	40
3	BACK END VARIABILITY	43
3.1	INTRODUCTION	43
3.2	COPPER CMP	44
3.3	COPPER ELECTROPLATING	47

3.4	MULTILEVEL COPPER INTERCONNECT VARIATION ...	50
3.5	INTERCONNECT LITHOGRAPHY AND ETCH VARIATION	52
3.6	DIELECTRIC VARIATION	53
3.7	BARRIER METAL DEPOSITION	54
3.8	COPPER AND VIA RESISTIVITY	55
3.9	COPPER LINE EDGE ROUGHNESS	56
3.10	CARBON NANOTUBE INTERCONNECTS	56
3.11	SUMMARY	57
4	ENVIRONMENTAL VARIABILITY	59
4.1	INTRODUCTION	59
4.2	IMPACT OF ENVIRONMENTAL VARIABILITY	60
4.3	ANALYSIS OF VOLTAGE VARIABILITY	65
4.3.1	Power Grid Analysis	66
4.3.2	Estimation of Power Variability	69
4.4	SYSTEMATIC ANALYSIS OF TEMPERATURE VARIABILITY	72
4.5	OTHER SOURCES OF VARIABILITY	80
4.6	SUMMARY	80

Part II Variability Characterization and Analysis		
5	TEST STRUCTURES FOR VARIABILITY	83
5.1	TEST STRUCTURES: CLASSIFICATION AND FIGURES OF MERIT	83
5.2	CHARACTERIZATION USING SHORT LOOP FLOWS	85
5.3	TRANSISTOR TEST STRUCTURES	90
5.4	DIGITAL TEST STRUCTURES	93
5.5	SUMMARY	96
6	STATISTICAL FOUNDATIONS OF DATA ANALYSIS AND MODELING	97
6.1	A BRIEF PROBABILITY PRIMER	98
6.2	EMPIRICAL MOMENT ESTIMATION	100
6.3	ANALYSIS OF VARIANCE AND ADDITIVE MODELS.....	102
6.4	CASE STUDIES: ANOVA FOR GATE LENGTH VARIABILITY	105
6.5	DECOMPOSITION OF VARIANCE INTO SPATIAL SIGNATURES	109
6.6	SPATIAL STATISTICS: DATA ANALYSIS AND MODELING	113
6.6.1	Measurements and Data Analysis.....	113
6.6.2	Modeling of Spatial Variability	116
6.7	SUMMARY	119

Part III Design Techniques for Systematic Manufacturability Problems

7	LITHOGRAPHY ENHANCEMENT TECHNIQUES	123
7.1	FUNDAMENTALS OF LITHOGRAPHY	124
7.2	PROCESS WINDOW ANALYSIS	129
7.3	OPTICAL PROXIMITY CORRECTION AND SRAFS	133
7.4	SUBRESOLUTION ASSIST FEATURES	136
7.5	PHASE SHIFT MASKING	138
7.6	NON-CONVENTIONAL ILLUMINATION AND IMPACT ON DESIGN	144
7.7	NOMINAL AND ACROSS PROCESS WINDOW HOT SPOT ANALYSIS	145
7.8	TIMING ANALYSIS UNDER SYSTEMATIC VARIABILITY	147
7.9	SUMMARY	149
8	ENSURING INTERCONNECT PLANARITY	151
8.1	OVERVIEW OF DUMMY FILL	152
8.2	DUMMY FILL CONCEPT	155
8.3	ALGORITHMS FOR METAL FILL	155
8.4	DUMMY FILL FOR STI CMP AND OTHER PROCESSES .	159
8.5	SUMMARY	159

Part IV Statistical Circuit Design

9	STATISTICAL CIRCUIT ANALYSIS	163
9.1	CIRCUIT PARAMETERIZATION AND SIMULATION	163
9.1.1	Introduction to Circuit Simulation	163
9.1.2	MOSFET Devices and Models	165
9.1.3	MOSFET Device Characterization	167
9.1.4	Statistical Device Characterization	170
9.1.5	Principal Component Analysis	171
9.2	WORST-CASE ANALYSIS	175
9.2.1	Worst-Case Analysis for Unbounded Parameters	176
9.2.2	Worst-Case Analysis Algorithm	177
9.2.3	Corner-Based Algorithm	179
9.2.4	Worst-Case Analysis Example	179
9.3	STATISTICAL CIRCUIT ANALYSIS	185
9.3.1	A Brief SRAM Tutorial	185
9.3.2	Monte Carlo Analysis	187
9.3.3	Response-Surface Analysis	189
9.3.4	Variance Reduction and Stratified Sampling Analysis	192

9.4	SUMMARY	195
10	STATISTICAL STATIC TIMING ANALYSIS	197
10.1	BASICS OF STATIC TIMING ANALYSIS	198
10.2	IMPACT OF VARIABILITY ON TRADITIONAL STATIC TIMING VERIFICATION	201
10.2.1	Increased Design Conservatism	201
10.2.2	Cost of Full Coverage and Danger of Missing Timing Violations	203
10.3	STATISTICAL TIMING EVALUATION	206
10.3.1	Problem Formulation and Challenges of SSTA	207
10.3.2	Block-Based Timing Algorithms	209
10.3.3	Path-Based Timing Algorithms	217
10.3.4	Parameter Space Techniques	223
10.3.5	Monte Carlo SSTA	226
10.4	STATISTICAL GATE LIBRARY CHARACTERIZATION ...	230
10.5	SUMMARY	233
11	LEAKAGE VARIABILITY AND JOINT PARAMETRIC YIELD	235
11.1	LEAKAGE VARIABILITY MODELING	235
11.2	JOINT POWER AND TIMING PARAMETRIC YIELD ESTIMATION	240
11.3	SUMMARY	245
12	PARAMETRIC YIELD OPTIMIZATION	247
12.1	LIMITATIONS OF TRADITIONAL OPTIMIZATION FOR YIELD IMPROVEMENT	247
12.2	STATISTICAL TIMING YIELD OPTIMIZATION	254
12.2.1	Statistical Circuit Tuning	254
12.2.2	Linear Programming under Uncertainty	259
12.3	TECHNIQUES FOR TIMING AND POWER YIELD IMPROVEMENT	266
12.4	SUMMARY	272
13	CONCLUSIONS.....	273
A	APPENDIX: PROJECTING VARIABILITY	275
	References	285
	Index	303