Contents to Volume 1

Foreword V

Contents to Volume 2 XIII

Preface XV

List of Contributors XIX

1Structure, Properties, and Preparation of Boronic Acid Derivatives:Overview of Their Reactions and Applications1

VII

Dennis G. Hall

- 1.1 Introduction and Historical Background 1
- 1.2 Structure and Properties of Boronic Acid Derivatives 2
- 1.2.1 General Types and Nomenclature of Boronic Acid Derivatives 2
- 1.2.2 Boronic Acids 3
- 1.2.2.1 Structure and Bonding 3
- 1.2.2.2 Physical Properties and Handling 8
- 1.2.2.3 Safety Considerations 9
- 1.2.2.4 Acidic Character 9
- 1.2.2.5 Chemical Stability 12
- 1.2.3 Boronic Acid Derivatives 15
- 1.2.3.1 Boroxines (Cyclic Anhydrides) 15
- 1.2.3.2 Boronic Esters 16
- 1.2.3.3 Acyloxy- and Diacyloxyboronates 25
- 1.2.3.4 Dialkoxyboranes and Other Heterocyclic Boranes 25
- 1.2.3.5 Diboronyl Esters 26
- 1.2.3.6 Azaborolidines and Other Boron–Nitrogen Heterocycles 27
- 1.2.3.7 Dihaloboranes and Dihydroalkylboranes 29
- 1.2.3.8 Trifluoro- and Trihydroxyborate Salts 30
- 1.3 Preparation of Boronic Acids and Their Esters 31
- 1.3.1 Arylboronic Acids 31
- 1.3.1.1 Electrophilic Trapping of Arylmetal Intermediates with Borates 31
- 1.3.1.2 Transmetalation of Aryl Silanes and Stannanes 41

VIII Contents

1	
1.3.1.3	Coupling of Aryl Halides with Diboronyl Reagents 42
1.3.1.4	Direct Boronation by Transition Metal-Catalyzed Aromatic C–H
	Functionalization 43
1.3.1.5	Cycloadditions of Alkynylboronates 43
1.3.1.6	Other Methods 43
1.3.2	Diboronic Acids 44
1.3.3	Heterocyclic Boronic Acids 44
1.3.4	Alkenylboronic Acids 45
1.3.4.1	Electrophilic Trapping of Alkenylmetal Intermediates with Borates 45
1.3.4.2	Transmetalation Methods 45
1.3.4.3	Transition Metal-Catalyzed Coupling between Alkenyl Halides/
	Triflates and Diboronyl Reagents 45
1.3.4.4	Hydroboration of Alkynes 55
1.3.4.5	Alkene Metathesis 58
1.3.4.6	Diboronylation and Silaboration of Unsaturated Compounds 59
1.3.4.7	Other Methods 60
1.3.5	Alkynylboronic Acids 60
1.3.6	Alkylboronic Acids 61
1.3.7	Allylic Boronic Acids 63
1.3.8	Chemoselective Transformations of Compounds Containing
	a Boronic Acid (Ester) Substituent 63
1.3.8.1	Oxidative Methods 64
1.3.8.2	Reductive Methods 64
1.3.8.3	Generation and Reactions of α -Boronyl-Substituted
	Carbanions and Radicals 66
1.3.8.4	Reactions of α -Haloalkylboronic Esters 68
1.3.8.5	Other Transformations 70
1.3.8.6	Protection of Boronic Acids for Orthogonal Transformations 72
1.4	Isolation and Characterization 73
1.4.1	Recrystallization and Chromatography 74
1.4.2	Solid Supports for Boronic Acid Immobilization and Purification 75
1.4.2.1	Diethanolaminomethyl Polystyrene 75
1.4.2.2	Other Solid-Supported Diol Resins 76
1.4.2.3	Soluble Diol Approaches 76
1.4.3	Analytical and Spectroscopic Methods for Boronic Acid Derivatives 76
1.4.3.1	Melting Points, Combustion Analysis, and HPLC 76
1.4.3.2	Mass Spectrometry 77
1.4.3.3	Nuclear Magnetic Resonance Spectroscopy 77
1.4.3.4	Other Spectroscopic Methods 78
1.5	Overview of the Reactions of Boronic Acid Derivatives 78
1.5.1	Metalation and Metal-Catalyzed Protodeboronation 78
1.5.2	Oxidative Replacement of Boron 79
1.5.2.1	Oxygenation 79
1.5.2.2	Amination and Amidation 81
1.5.2.3	Halodeboronation 81
1.5.3	Carbon–Carbon Bond Forming Processes 85
1.3.3	Carbon Carbon Dona Forming Frocesses 05

	Comonis
1.5.3.1	Transition Metal-Catalyzed Cross-Coupling with Carbon
	Halides and Surrogates (Suzuki–Miyaura Cross-Coupling) 85
1.5.3.2	Transition Metal-Catalyzed Insertions, Cycloisomerizations, and
	C–H Functionalizations Based on Transmetalation of Boronic Acids 88
1.5.3.3	Heck-Type Coupling to Alkenes and Alkynes 90
1.5.3.4	Rhodium- and Other Transition Metal-Catalyzed Additions to
	Alkenes, Carbonyl Compounds, and Imine Derivatives 90
1.5.3.5	Diol-Catalyzed Additions of Boronic Esters to Unsaturated
	Carbonyl Compounds and Acetals 92
1.5.3.6	Allylation of Carbonyl Compounds and Imine Derivatives 93
1.5.3.7	Uncatalyzed Additions of Boronic Acids to Imines and Iminiums 93
1.5.4	Carbon–Heteroatom Bond Forming Processes 94
1.5.4.1	Copper-Catalyzed Coupling with Nucleophilic Oxygen
	and Nitrogen Compounds 94
1.5.5	Other Reactions 94
1.6	Overview of Other Applications of Boronic Acid Derivatives 97
1.6.1	Use as Reaction Promoters and Catalysts 97
1.6.2	Use as Protecting Groups for Diols and Diamines 99
1.6.3	Use as Supports for Immobilization, Derivatization, Affinity
	Purification, Analysis of Diols, Sugars, and Glycosylated Proteins
	and Cells 100
1.6.4	Use as Receptors and Sensors for Carbohydrates and Other
	Small Molecules 102
1.6.5	Use as Antimicrobial Agents and Enzyme Inhibitors 103
1.6.6	Use in Neutron Capture Therapy for Cancer 105
1.6.7	Use in Transmembrane Transport 105
1.6.8	Use in Bioconjugation and Labeling of Proteins and Cell Surface 106
1.6.9	Use in Chemical Biology 107
1.6.10	Use in Materials Science and Self-Assembly 108
	References 109
2	Metal-Catalyzed Borylation of C–H and C–Halogen Bonds of
	Alkanes, Alkenes, and Arenes for the Synthesis of Boronic Esters 135
	Tatsuo Ishiyama and Norio Miyaura
2.1	Introduction 135
2.2	Borylation of Halides and Triflates via Coupling of H–B and B–B
	Compounds 137
2.2.1	Borylation of Aryl Halides and Triflates 138
2.2.2	Alkenyl Halides and Triflates 143
2.2.3	Allylic Halides, Allylic Acetates, and Allylic Alcohols 145
2.2.4	Benzylic Halides 148
2.3	Borylation via C–H Activation 148
2.3.1	Aliphatic C–H Bonds 148
2.3.2	Alkenyl C–H Bonds 151
2.3.3	Aromatic C–H Bonds 153
2.4	Catalytic Cycle 159

2.4 Catalytic Cycle 159

X Contents

2.5	Summary 161
	References 161
3	Transition Metal-Catalyzed Element-Boryl Additions to Unsaturated
5	Organic Compounds 171
	Michinori Suginome and Toshimichi Ohmura
3.1	Introduction 171
3.2	Diboration 172
3.2.1	Diboron Reagents for Diboration 172
3.2.2	Diboration of Alkynes 173
3.2.3	Diboration of Alkenes, Allenes, 1,3-Dienes, and
	Methylenecyclopropanes 176
3.2.4	Synthetic Applications of Diboration Products 183
3.3	Silaboration 185
3.3.1	Silylborane Reagents for Silaboration 185
3.3.2	Silaboration of Alkynes 187
3.3.3	Silaboration of Alkenes, Allenes, 1,3-Dienes, and
	Methylenecyclopropanes 191
3.3.4	Synthetic Application of Silaboration Products 200
3.4	Carboboration 202
3.4.1	Direct Addition: Cyanoboration and Alkynylboration 203
3.4.2	Transmetalative Carboboration 205
3.5	Miscellaneous Element-Boryl Additions 207
3.6	Conclusion 208
	References 208
4	The Contemporary Suzuki-Miyaura Reaction 213
	Cory Valente and Michael G. Organ
4.1	Introduction 213
4.1.1	Preamble and Outlook 213
4.1.2	A Brief History 214
4.1.3	Mechanistic Aspects 214
4.2	Developments Made in the Coupling of Nontrivial Substrates 215
4.2.1	Rational Design of Ligands for Use in the Suzuki–Miyaura
	Reaction 215
4.2.1.1	Organophosphine Ligands and Properties 217
4.2.1.2	N-Heterocyclic Carbene Ligands and their Properties 219
4.2.2	The Suzuki–Miyaura Cross-Coupling of Challenging Aryl Halides 220
4.2.2.1	Overview of Challenges 220
4.2.2.2	Organophosphine-Derived Catalysts 221
4.2.2.3	NHC-Derived Catalysts 228
4.2.3	The Suzuki–Miyaura Reaction Involving Unactivated Alkyl Halides 234
4.2.3.1	Associated Difficulties 234
4.2.3.2	Cross-Couplings Promoted by Phosphines and Amine-Based
	Ligands 235

- 4.2.3.3 Cross-Coupling-Promoted NHC Ligands 240
- 4.3 Asymmetric Suzuki–Miyaura Cross-Couplings 241
- 4.3.1 Achieving Axial Chirality in the Suzuki–Miyaura Reaction 241
- 4.3.1.1 Axial Chirality Induced by Chiral Ligands/Catalysts 241
- 4.3.1.2 Axial Chirality Induced by Point Chirality 244
- 4.3.1.3 Axial Chirality Induced by Planar Chirality 246
- 4.3.2 Achieving Point Chirality in the Suzuki–Miyaura Reaction 246
- 4.4 Iterative Suzuki–Miyaura Cross-Couplings 248
- 4.4.1 *ortho* Metalation–Cross-coupling Iterations 248
- 4.4.2 Triflating–Cross-Coupling Iterations 248
- 4.4.3 Iterative Cross-Couplings via Orthogonal Reactivity 249
- 4.4.3.1 Bifunctional Electrophiles 249
- 4.4.3.2 Bifunctional Organoboranes 252
- 4.5 Conclusions and Future Outlook 256 References 257

5 Rhodium- and Palladium-Catalyzed Asymmetric Conjugate Additions of Organoboronic Acids 263

- Guillaume Berthon-Gelloz and Tamio Hayashi
- 5.1 Introduction 263
- 5.2 Rh-Catalyzed Enantioselective Conjugate Addition of Organoboron Reagents 263
- 5.2.1 α,β -Unsaturated Unsaturated Ketones 264
- 5.2.1.1 A Short History 264
- 5.2.1.2 Mechanism 264
- 5.2.1.3 Model for Enantioselection 266
- 5.2.1.4 Organoboron Sources Other Than Boronic Acids 266
- 5.2.1.5 Rh Precatalysts 269
- 5.2.1.6 Ligand Systems 269
- 5.2.1.7 α,β-Unsaturated Aldehydes 278
- 5.2.2 Enantioselective Addition to α , β -Unsaturated Esters and Amides 279
- 5.2.2.1 Diastereoselective Conjugate Addition 282
- 5.2.2.2 Fumarate and Maleimides 284
- 5.2.2.3 Synthetically Useful Acceptors 286
- 5.2.2.4 Conjugate Additions of Boryl and Silyl Groups 286
- 5.2.3 Addition to Other Electron-Deficient Alkenes 288
- 5.2.3.1 Arylmethylene Cyanoacetates 288
- 5.2.3.2 Alkenylphosphonates 288
- 5.2.3.3 Nitroalkene 288
- 5.2.3.4 Sulfones 289
- 5.2.3.5 Addition to *cis*-Allylic Alcohols 291
- 5.2.3.6 1,4-Addition/Enantioselective Protonation 291
- 5.2.4 1,6-Conjugate Additions 294
- 5.2.5 Rh-Catalyzed Enantioselective Conjugate Addition with Other Organometallic Reagents 296

XII Contents

5.2.6	Rh-Catalyzed Tandem Processes 297
5.2.6.1	Tandem Enantioselective Conjugate Addition/Aldol Reaction 297
5.2.6.2	Tandem Carborhodation/Conjugate Addition 298
5.3	Pd-Catalyzed Enantioselective Conjugate Addition of Organoboron
	Reagents 299
5.3.1	Introduction 299
5.3.2	Addition to α,β -Unsaturated Ketones 300
5.3.3	Addition to α , β -Unsaturated Esters, Amides, and Aldehydes 304
5.3.4	Palladium-Catalyzed Tandem Processes 305
5.4	Conclusions 306
	References 307
6	Recent Advances in Chan–Lam Coupling Reaction:
	Copper-Promoted C-Heteroatom Bond Cross-Coupling
	Reactions with Boronic Acids and Derivatives 315
	Jennifer X. Qiao and Patrick Y.S. Lam
6.1	General Introduction 315
6.2	C–O Cross-Coupling with Arylboronic Acids 316
6.2.1	Intermolecular C–O Cross-Coupling 316
6.2.2	Intramolecular C–O Cross-Coupling 320
6.3	C–N Cross-Coupling with Arylboronic Acids 321
6.3.1	C–N (Nonheteroarene NH) Cross-Coupling 321
6.3.1.1	Application of Chan–Lam Cross-Coupling in Solid-Phase Synthesis 324
6.3.2	C–N (Heteroarene) Cross-Coupling 324
6.3.2.1	Factor Xa Inhibitors 326
6.3.2.2	Purines 326
6.3.2.3	Heteroarene–Heteroarene Cross-Coupling 329
6.3.3	Intramolecular C–N Cross-Coupling 330
6.3.4	Catalytic Copper-Mediated C–N Cross-Coupling 331
6.3.5	Additional N-Containing Substrates in Chan–Lam Cross-Coupling 332
6.4	Substrate Selectivity and Reactivity in Chan-Lam Cross-Coupling
	Reaction 335
6.5	C–N and C–O Cross-Coupling with Alkenylboronic Acids 336
6.6	C–N and C–O Cross-Coupling with Boronic Acid Derivatives 338
6.6.1	Boroxines, Boronic Esters, and Trifluoroborate Salts 338
6.6.2	Alkylboronic Acids 343
6.7	C–S and C–Se/C–Te Cross-Coupling 346
6.8	Mechanistic Considerations 349
6.8.1	Empirical Observations 349
6.8.2	General Mechanistic Observations 351
6.8.3	Mechanistic Study of the Catalytic Reaction 352
6.9	Other Organometalloids 354
6.10	Conclusion 355
6.11	Note Added in Proof 355
	References 357

Contents to Volume 2

- 7 Transition Metal-Catalyzed Desulfitative Coupling of Thioorganic Compounds with Boronic Acids 363 Ethel C. Garnier-Amblard and Lanny S. Liebeskind
- 8 Catalytic Additions of Allylic Boronates to Carbonyl and Imine Derivatives 393 Tim G. Elford and Dennis G. Hall
- 9 Recent Advances in Nucleophilic Addition Reactions of Organoboronic Acids and Their Derivatives to Unsaturated C–N Functionalities 427 Timothy R. Ramadhar and Robert A. Batey
- 10 Asymmetric Homologation of Boronic Esters with Lithiated Carbamates, Epoxides, and Aziridines 479 Matthew P. Webster and Varinder K. Aggarwal
- 11 Organotrifluoroborates: Organoboron Reagents for the Twenty-First Century 507 Gary A. Molander and Ludivine Jean-Gérard
- 12 Borate and Boronic Acid Derivatives as Catalysts in Organic Synthesis 551 Joshua N. Payette and Hisashi Yamamoto
- 13 Applications of Boronic Acids in Chemical Biology and Medicinal Chemistry 591 Nanting Ni and Binghe Wang
- 14Boronic Acids in Materials Chemistry621Jie Liu and John J. Lavigne

Index 677