

## Contents

**Preface** *XI*

**Acronyms** *XXIII*

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Main Concepts and Issues	2
1.2	Self-Organized Nanoworld, Commonsense Science of the Small and Socio-Economic Push	7
1.3	Nature's Plasma Nanofab and Nanotechnology Research Directions	21
1.4	Deterministic Nanofabrication and Plasma Nanoscience	28
1.5	Structure of the Monograph and Advice to the Reader	43
<b>2</b>	<b>What Makes Low-Temperature Plasmas a Versatile Nanotool?</b>	<b>49</b>
2.1	Basic Ideas and Major Issues	50
2.2	Plasma Nanofabrication Concept	55
2.3	Useful Plasma Features for Nanoscale Fabrication	66
2.4	Choice and Generation of Building and Working Units	72
2.5	Effect of the Plasma Sheath	81
2.6	How Plasmas Affect Elementary Surface Processes	97
2.7	Concluding Remarks	105
<b>3</b>	<b>Specific Examples and Practical Framework</b>	<b>107</b>
3.1	Semiconducting Nanofilms and Nanostructures	107
3.2	Carbon-Based Nanofilms and Nanostructures	117
3.3	Practical Framework – Bridging Nine Orders of Magnitude	133
3.4	Concluding Remarks	140
<b>4</b>	<b>Generation of Building and Working Units</b>	<b>145</b>
4.1	Species in Methane-Based Plasmas for Synthesis of Carbon Nanostructures	146

4.1.1	Experimental Details	149
4.1.2	Basic Assumptions of the Model	152
4.1.3	Particle and Power Balance in Plasma Discharge	153
4.1.4	Densities of Neutral and Charged Species	155
4.1.4.1	Effect of RF Power	156
4.1.4.2	Effect of Argon and Methane Dilution	158
4.1.5	Deposited Neutral and Ion Fluxes	159
4.1.6	Most Important Points and Summary	162
4.2	Species in Acetylene-Based Plasmas for Synthesis of Carbon Nanostructures	164
4.2.1	Formulation of the Problem	165
4.2.2	Number Densities of the Main Discharge Species	167
4.2.3	Fluxes of Building and Working Units	171
4.3	Nanocluster and Nanoparticle Building Units	177
4.3.1	Nano-Sized Building Units from Reactive Plasmas	177
4.3.2	Nanoparticle Generation: Other Examples	182
4.4	Concluding Remarks	194
<b>5</b>	<b>Transport, Manipulation and Deposition of Building and Working Units</b>	<b>199</b>
5.1	Microscopic Ion Fluxes During Nanoassembly Processes	200
5.1.1	Formulation and Model	202
5.1.2	Numerical Results	204
5.1.3	Interpretation of Numerical Results	209
5.2	Nanoparticle Manipulation in the Synthesis of Carbon Nanostructures	213
5.2.1	Nanoparticle Manipulation: Experimental Results	215
5.2.2	Nanoparticle Manipulation: Numerical Model	220
5.3	Selected-Area Nanoparticle Deposition Onto Microstructured Surfaces	227
5.3.1	Numerical Model and Simulation Parameters	228
5.3.2	Selected-Area Nanoparticle Deposition	231
5.3.3	Practical Implementation Framework	237
5.4	Electrostatic Nanoparticle Filter	239
5.5	Concluding Remarks	244
<b>6</b>	<b>Surface Science of Plasma-Exposed Surfaces and Self-Organization Processes</b>	<b>249</b>
	<i>K. Ostrikov and I. Levchenko</i>	
6.1	Synthesis of Self-Organizing Arrays of Quantum Dots: Objectives and Approach	251

6.2	Initial Stage of Ge/Si Nanodot Formation Using Nanocluster Fluxes	272
6.2.1	Physical Model and Numerical Details	273
6.2.2	Physical Interpretation and Relevant Experimental Data	277
6.3	Binary $\text{Si}_x\text{C}_{1-x}$ Quantum Dot Systems: Initial Growth Stage	282
6.3.1	Adatom Fluxes at Initial Growth Stages of $\text{Si}_x\text{C}_{1-x}$ Quantum Dots	282
6.3.2	Control of Core-Shell Structure and Elemental Composition of $\text{Si}_x\text{C}_{1-x}$ Quantum Dots	294
6.4	Self-Organization in Ge/Si Nanodot Arrays at Advanced Growth Stages	301
6.4.1	Model of Nanopattern Development	303
6.4.2	Ge/Si QD Size and Positional Uniformity	307
6.4.3	Self-Organization in Ge/Si QD Patterns: Driving Forces and Features	310
6.5	Self-Organized Nanodot Arrays: Plasma-Specific Effects	314
6.5.1	Matching Balance and Supply of BUs: a Requirement for Deterministic Nanoassembly	315
6.5.2	Other General Considerations	317
6.5.3	Plasma-Related Effects at Initial Growth Stages	319
6.5.4	Separate Growth of Individual Nanostructures	321
6.5.5	Self-Organization in Large Nanostructure Arrays	327
6.6	Concluding Remarks	332
<b>7</b>	<b>Ion-Focusing Nanoscale Objects</b>	<b>341</b>
7.1	General Considerations and Elementary Processes	343
7.2	Plasma-Specific Effects on the Growth of Carbon Nanotubes and Related Nanostructures	356
7.2.1	Plasma-Related Effects on Carbon Nanofibers	357
7.2.2	Effects of Ions and Atomic Hydrogen on the Growth of SWCNTs	364
7.3	Plasma-Controlled Reshaping of Carbon Nanostructures	373
7.3.1	Self-Sharpening of Platelet-Structured Nanocones	373
7.3.2	Plasma-Based Deterministic Shape Control in Nanotip Assembly	380
7.4	Self-Organization of Large Nanotip Arrays	385
7.5	From Non-Uniform Catalyst Islands to Uniform Nanoarrays	391
7.5.1	Experiment and Film Characterization	393
7.5.2	Growth Model and Numerical Simulations	397
7.6	Other Ion-Focusing Nanostructures	402
7.7	Concluding Remarks	407

<b>8</b>	<b>Building and Working Units at Work: Applications</b>	<b>415</b>
8.1	Plasma-Based Post-Processing of Nanoarrays	416
8.1.1	Post-Processing of Nanotube Arrays	418
8.1.2	Functional Monolayer Coating of Nanorod Arrays	422
8.2	i-PVD of Metal Nanodot Arrays Using Nanoporous Templates	427
8.3	Metal Oxide Nanostructures: Plasma-Generated BUs Create Other BUs on the Surface	434
8.4	Biocompatible TiO <sub>2</sub> Films: How Building Units Work	440
8.4.1	TiO <sub>2</sub> Film Deposition and Characterization	442
8.4.2	<i>In Vitro</i> Apatite Formation	446
8.4.3	Growth Kinetics: Building Units at Work	448
8.4.4	Building Units <i>In Vitro</i> : Inducing Biomimetic Response	453
8.5	Concluding Remarks	456
<b>9</b>	<b>Conclusions and Outlook</b>	<b>461</b>
9.1	Determinism and Higher Complexity	464
9.2	Plasma-Related Features and Areas of Competitive Advantage	467
9.3	Outlook for the Future	470
9.4	Final Remarks	479
<b>10</b>	<b>Appendix A. Reactions and Rate Equations</b>	<b>483</b>
10.1	Plasmas of Ar + H <sub>2</sub> + CH <sub>4</sub> Gas Mixtures (Section 4.1)	483
10.2	Plasmas of Ar + H <sub>2</sub> + C <sub>2</sub> H <sub>2</sub> Gas Mixtures (Section 4.2)	486
<b>11</b>	<b>Appendix B. Why Plasma-based Nanoassembly: Further Reasons</b>	<b>491</b>
11.1	Carbon Nanotubes and Related Structures	491
11.2	Semiconductor Nanostructures and Nanomaterials	493
11.3	Other Nanostructures and Nanoscale Objects	494
11.4	Materials with Nanoscale Features	496
11.5	Plasma-Related Issues and Fabrication Techniques	497
	<b>References</b>	<b>499</b>
	<b>Index</b>	<b>529</b>