

Contents

List of Contributors *XI*

Preface *XVII*

1	Introduction	<i>1</i>
	<i>Matthias F. Kling, Brady C. Steffl, and Peter Hommelhoff</i>	
1.1	Attosecond Tools	<i>1</i>
1.1.1	Strong Field Control Using Laser Pulses with Well-Defined Waveforms	<i>1</i>
1.1.2	Attosecond Light Pulses: Tracing Electron Dynamics	<i>3</i>
1.2	Solids in Strong Fields	<i>4</i>
1.3	Attosecond Physics in Isolated Nanosystems	<i>4</i>
1.4	Attosecond Physics on Nanostructured Surfaces	<i>6</i>
1.5	Perspectives	<i>7</i>
	References	<i>8</i>
2	Nano-Antennae Assisted Emission of Extreme Ultraviolet Radiation	<i>11</i>
	<i>Nils Pfullmann, Monika Noack, Carsten Reinhardt, Milutin Kovacev, and Uwe Morgner</i>	
2.1	Introduction and Motivation	<i>11</i>
2.2	Experimental Idea	<i>12</i>
2.3	High-Order Harmonic Generation	<i>14</i>
2.3.1	Semi-Classical Model	<i>15</i>
2.3.2	Macroscopic Effects/Phase-Matching	<i>16</i>
2.3.3	Phase-Matching in the Case of Optical Antennas	<i>18</i>
2.3.4	Field Inhomogeneities	<i>19</i>
2.4	Plasmonics in Intense Laser Fields	<i>20</i>
2.5	Experiments	<i>23</i>
2.5.1	Historical Overview	<i>23</i>
2.5.2	Own Experiments	<i>24</i>

2.5.2.1	Experimental Set-Up	24
2.5.2.2	Experimental Results	26
2.5.2.3	Gas Density	28
2.5.2.4	Spectra	29
2.6	Conclusion and Outlook	31
	References	33
3	Ultrafast, Strong-Field Plasmonic Phenomena	39
	<i>Péter Dombi and Abdulhakem Y. Elezzabi</i>	
3.1	Introduction	39
3.2	Ultrafast Photoemission and Electron Acceleration in Surface Plasmon Fields	43
3.2.1	Photoemission Mechanisms	43
3.2.1.1	Linear Photoemission	43
3.2.1.2	Nonlinear Photoemission and Photocurrents	43
3.2.1.3	Distinction of the Photoemission Regimes	44
3.2.1.4	Multiphoton-Induced Photoemission and Photocurrents	44
3.2.1.5	Above-Threshold Photoemission	46
3.2.1.6	Tunneling Photoemission and Currents	46
3.2.2	Particle Acceleration in Evanescent Surface Plasmon Fields	47
3.3	Research on Surface Plasmon-Enhanced Photoemission and Electron Acceleration	48
3.3.1	Photocurrent Enhancement	48
3.3.2	Strong-Field Photoemission in Plasmonic Fields	50
3.3.3	Electron Acceleration in Plasmonic Fields	51
3.3.4	Modeling and Discussion	53
3.3.4.1	Modeling Tools	53
3.3.4.2	Electromagnetic Wave Dynamics of the Surface Plasmon Field	55
3.3.4.3	Electron Emission Channels and Currents Induced by the Plasmonic Fields	57
3.3.4.4	Particle Acceleration in the Evanescent Field	58
3.3.4.5	Model Results for High-Energy Electron Generation	60
3.3.5	Time-Resolved Studies of Ultrashort Surface Plasmon Wavepackets	62
3.3.5.1	Experiments	62
3.3.5.2	Autocorrelation Reconstruction Without Fitting Parameters	64
3.3.6	The Carrier-Envelope Phase in Nanoplasmonic Electron Acceleration	66
3.3.7	Non-ponderomotive Effects and Quiver Motion Quenching in Nano-Localized Fields	69
3.3.8	Nanoplasmonic Photoemission from Metal Nanoparticles	75
3.4	Conclusions	79
	Acknowledgments	81
	References	81

4	Ultrafast Dynamics in Extended Systems	87
	<i>Ulf Saalmann and Jan-Michael Rost</i>	
4.1	Introduction—Why Ultrafast Electron Dynamics in Extended Systems?	87
4.2	Multi-Photon Absorption in Extended Systems	89
4.2.1	General Evolution of an Extended System Exposed to an Intense Laser Pulse	89
4.2.2	A Unified Picture on Energy Absorption from Intense Light Fields	91
4.2.3	Hard and Soft Recollisions in Atomic Systems	93
4.2.4	Extended Systems and Optical Swingbys	94
4.2.5	Resonant Absorption by Electron Motion Out of Phase with the Light Field	97
4.3	Coulomb Complexes: A Simple Approach to Ultrafast Electron Dynamics in FEL-Irradiated Extended Systems	99
4.3.1	Photo-Activation	101
4.3.2	The Ionic Background Potential	102
4.3.3	Formation of the Electron Spectra	103
4.3.4	Scaling in the Dynamics of Coulomb Complexes	105
4.4	Nano-Plasma Transients on the Femtosecond Scale	106
4.4.1	Creating and Probing a Dense Non-equilibrium Nano-Plasma by Sub-femtosecond Pump-Probe Pulses	106
4.4.2	Ultrafast Collective Electron Dynamics in Composite Systems	111
4.5	Summary	115
	Acknowledgments	115
	References	116
5	Light Wave Driven Electron Dynamics in Clusters	119
	<i>Charles Varin, Christian Peltz, Thomas Brabec, and Thomas Fennel</i>	
5.1	Introduction	119
5.2	Resolving Light-Matter Interactions on the Atomic-Scale	120
5.2.1	Theoretical Foundations of Classical Light-Matter Interaction	120
5.2.2	Molecular Dynamics	125
5.2.3	The Particle-in-Cell Method	125
5.2.4	The Microscopic Particle-in-Cell Method	126
5.3	Fundamentals of the Microscopic Particle-in-Cell Approach	127
5.3.1	Theoretical Background	127
5.3.2	Numerical Implementation	130
5.3.2.1	The Electromagnetic Solver	130
5.3.2.2	Gaussian-Shape Particles and Microscopic Force Correction	131
5.3.2.3	Linear Scaling with MicPIC	133
5.3.2.4	Typical Numerical Parameters	134
5.3.3	Link to Molecular Dynamics	134
5.3.4	Link to Continuum Models	135
5.4	Microscopic Analysis of Laser-Driven Nanoclusters	137

5.4.1	Nanoplasma Formation in a Small Rare-Gas Cluster	138
5.4.2	Cluster Dynamics in the Linear Response Regime	140
5.4.3	Linear Absorption and Scattering of Light	142
5.4.4	Competition of Bulk and Surface Effects with Radiation Damping in Resonant Clusters	144
5.4.5	Microscopic Analysis of Nonlinear Light Scattering	145
5.5	Conclusions	149
	References	150
6	From Attosecond Control of Electrons at Nano-Objects to Laser-Driven Electron Accelerators	155
	<i>Frederik Süßmann, Matthias F. Kling, and Peter Hommelhoff</i>	
6.1	Attosecond Control of Electrons at Nanoscale Metal Tips	155
6.1.1	Multi-Photon Ionization	156
6.1.1.1	Coherent Effects	157
6.1.1.2	Light Shifts	157
6.1.2	Sub-Cycle Dynamics	158
6.1.2.1	Recollision and Rescattering	158
6.1.2.2	CEP Effects and Matter Wave Interference	160
6.1.2.3	Modeling of Strong-Field Physics at a Metal Tip – Instructively	160
6.1.2.4	Modeling of Strong-Field Physics at a Metal Tip – Microscopically	161
6.1.3	Optical Near-Field Sensor	162
6.1.4	A Sub-Laser-Cycle Duration Electron Source?	164
6.2	Experiments on Dielectric Nanospheres	165
6.2.1	Modifications by Collective Excitations/Space Charge	165
6.2.2	CEP-Dependent Photoemission from SiO ₂ Nanospheres	166
6.2.3	Theoretical Modeling of the Photoemission/Acceleration Process	169
6.3	The Influence of the Spatial Field Distribution on Photoelectron Spectra	171
6.3.1	Transition from Dipolar to Multipolar Response	172
6.3.1.1	Mie Solution for Nanospheres	172
6.3.2	Angular Resolved Photoemission from SiO ₂ Nanospheres	176
6.4	Time Resolved Pump-Probe Schemes	177
6.4.1	The Attosecond Streak Camera	177
6.4.2	Attosecond Streaking from Nanostructures	179
6.4.3	The Regimes of Near-Field Streaking	179
6.4.4	Simulated Streaking Spectrograms for Au Spheres	182
6.5	Electron Acceleration with Laser Light at Dielectric Nano-Gratings	185
6.5.1	Near-Field Mode Acceleration	186
6.5.2	Proof-of-Concept Data	189
6.5.3	Outlook on Future Acceleration Mechanisms	190
	References	191

7	Theory of Solids in Strong Ultrashort Laser Fields	197
	<i>Vadym Apalkov and Mark I. Stockman</i>	
7.1	Interaction of Ultrafast Laser Pulse with Solids: Coherent and Incoherent Electron Dynamics	197
7.2	One Dimensional Tight Binding Model	200
7.2.1	Single-Band Approximation	201
7.2.1.1	Exact Solution	201
7.2.1.2	Wannier–Stark Levels	202
7.2.2	Multi-Band Approximation	210
7.2.3	Description of Electron Dynamics in Terms of the Wannier–Stark States	213
7.2.3.1	Wannier–Stark States of Two-Band System	213
7.2.3.2	Adiabatic and Diabatic Electron Dynamics	217
7.2.4	Results of Numerical Calculations	221
7.2.4.1	Electron Dynamics and Breakdown of Dielectric	221
7.2.4.2	Enhancement of the Dielectric Response of a Solid in a Strong Laser Pulse	225
7.2.4.3	Electrical Current and Charge Transfer	227
7.3	3D Model of Electron Dynamics	229
	References	232
8	Controlling and Tracking Electric Currents with Light	235
	<i>Agustin Schiffrin, Tim Paasch-Colberg, and Martin Schultze</i>	
8.1	Introduction	235
8.2	Electric Field Control of Currents: From the Vacuum Tube to the Transistor	235
8.3	Generating Electric Currents with Light: An Ultrabroad-Bandwidth Control Tool	239
8.4	Optical Field Control of Electric Current in Large Bandgap Materials	243
8.5	Attosecond Probing of the Strong-Field-Induced Changes of the Dielectric Electronic Properties	262
8.6	Detection of the Carrier-Envelope Phase Using Optical-Field-Induced Currents	271
8.7	Toward Ultrafast Photoactive Logic Circuits?	273
	References	275
9	Ultrafast Nano-Focusing for Imaging and Spectroscopy with Electrons and Light	281
	<i>Christoph Lienau, Markus Raschke, and Claus Ropers</i>	
9.1	Introduction	281
9.2	Adiabatic Nanofocusing	282
9.2.1	Introduction	282
9.2.2	Results	286

9.2.2.1	Experimental Demonstration of Adiabatic Nanofocusing on a Tip	286
9.2.2.2	Nano-Spectroscopic Imaging	289
9.2.2.3	Femtosecond Optical Control	291
9.2.3	Quantum Coherent Control of a Single Emitter	295
9.3	Nanometer-Sized Localized Electron Sources	297
9.3.1	Introduction	297
9.3.2	Processes in Localized Photoemission at Metal Nanotips	299
9.3.3	Near-Field Imaging Based on Localized Multiphoton Photoemission	301
9.3.4	Transition to the Strong-Field Regime	302
9.3.5	Localization Effects in the Strong-Field Regime	303
9.3.6	Angle-Resolved Photoemission	309
9.4	Summary and Conclusion	313
	Acknowledgments	314
	References	314
10	Imaging Localized Surface Plasmons by Femtosecond to Attosecond Time-Resolved Photoelectron Emission Microscopy – “ATTO-PEEM”	325
	<i>Soo Hoon Chew, Kellie Pearce, Christian Späth, Alexander Guggenmos, Jürgen Schmidt, Frederik Süßmann, Matthias F. Kling, Ulf Kleineberg, Erik Mårzell, Cord L. Arnold, Eleonora Lorek, Piotr Rudawski, Chen Guo, Miguel Miranda, Fernando Ardana, Johan Mauritsson, Anne L’Huillier, and Anders Mikkelsen</i>	
10.1	Introduction	325
10.2	Time-Resolved Multiphoton PEEM with Femtosecond Time Resolution	326
10.2.1	Observation of Surface Plasmon Enhanced “Hot Spot” Photoemission in fs-PEEM	326
10.2.2	Interferometric Time-Resolved fs-PEEM	327
10.2.3	Adaptive Sub-wavelength Control of Nanooptical Fields	328
10.2.4	Coherent Two-Dimensional Nanoscopy	328
10.3	The “ATTO-PEEM”	329
10.3.1	Theoretical Description of the Attosecond Nanoplasmonic Field Microscope	330
10.3.2	High Harmonic PEEM with Single Attosecond XUV Pulses	332
10.3.3	PEEM with High-Order Harmonics: Attosecond Pulse Trains and 1–200 kHz Repetition Rate Light Sources	338
10.3.3.1	Experimental Setup and Requirements	338
10.3.3.2	XUV Imaging	350
	References	361
	Index	365