

Contents

Foreword *xv*

Preface *xvii*

1	2D Electronic Circuits for Sensing Applications	1
	<i>Diogo Baptista, Ivo Colmiais, Vitor Silva, Pedro Alpuim, and Paulo M. Mendes</i>	
1.1	Introduction	1
1.2	Graphene Inductors	3
1.2.1	Modeling of Graphene Inductors	4
1.3	Graphene Capacitors	5
1.3.1	Modeling Graphene Capacitors	8
1.4	2D Material Transistors	9
1.4.1	Most Common Topologies for Transistors	10
1.4.2	Modeling of 2D Materials-Based Transistors	11
1.5	2D Material Diodes	15
1.5.1	Most Common Topologies	16
1.5.2	Modeling of 2D Materials-Based Diodes	17
1.6	Graphene Devices	18
1.6.1	Graphene Frequency Multipliers	18
1.6.2	Graphene Mixers	18
1.6.3	Graphene Oscillators	19
1.6.3.1	Ring Oscillators	19
1.6.3.2	LC Tank Oscillators	19
1.7	Conclusion	19
	References	20
2	Large Graphene Oxide for Sensing Applications	25
	<i>Jingfeng Huang, J. Amanda Ong, and I.Y. Alfred Tok</i>	
2.1	Graphene Oxide (GO)	25
2.2	GO as Biosensors	25
2.3	Large GO	26
2.4	Mechanism of Large GO via Modified Hummers Method	27
2.5	Large GO (Modified Hummers Method) Biosensors	28

2.6	Mechanism of Large GO via Reduced GO Growth	29
2.7	Large GO (Reduced GO Growth) Biosensors	34
2.8	Conclusion	38
2.9	Further Developments	38
	References	39
3	Solution-Gated Reduced Graphene Oxide FETs: Device Fabrication and Biosensors Applications	43
	<i>Nilton C. S. Vieira, Bianca C. S. Ribeiro, Rodrigo V. Blasques, Bruno C. Janegitz, Fabrício A. dos Santos, and Valtencir Zucolotto</i>	
3.1	Introduction	43
3.2	Graphene, Graphene Oxide, and Reduced Graphene Oxide	45
3.2.1	Chemical Reduction	48
3.2.2	Thermal Reduction	49
3.2.3	Electrochemical Reduction	51
3.3	rGO-Based Solution-Gated FETs	52
3.3.1	Manufacturing Strategies	53
3.4	Applications of rGO SG-FETs as Biosensors	57
3.4.1	rGO Functionalization	59
3.4.2	Enzymatic Biosensors	60
3.4.3	Affinity Biosensors	61
3.4.4	Debye Length Screening and How to Overcome It	63
3.5	Final Remarks and Challenges	64
	Acknowledgments	65
	References	65
4	Graphene-Based Electronic Biosensors for Disease Diagnostics	71
	<i>Ahmar Hasnain and Alexey Tarasov</i>	
4.1	Introduction	71
4.1.1	A Promise for Diagnostics	71
4.1.2	Principle of Graphene FET Sensor	72
4.2	Device Fabrication Process	75
4.2.1	Graphene Synthesis	75
4.2.2	Graphene Transfer Over Substrates	76
4.2.3	Fabrication of GFET	77
4.2.4	New Developments	78
4.3	Functionalization and Passivation	78
4.3.1	Probe Molecules	79
4.3.2	Immobilization of Probe Molecules	80
4.3.3	Debye Length	81
4.3.4	Passivation	82
4.4	CVD GFETs for Diagnostics	83
4.4.1	Graphene-Based FET Biosensors for Nucleic Acids	83
4.4.2	Graphene-Based FET Biosensors for Antibody–Antigen Interactions	85

4.4.3	Graphene-Based FET Biosensors for Enzymatic Biosensors	87
4.4.4	Graphene-Based FET Biosensors for Sensing of Small Ions	90
4.5	Discussion	92
4.5.1	Summary	92
4.5.2	Challenges	92
4.5.3	Future Perspectives	93
	References	93
5	Graphene Field-Effect Transistors: Advanced Bioelectronic Devices for Sensing Applications	103
	<i>Kyung Ho Kim, Hyun Seok Song, Oh Seok Kwon, and Tai Hyun Park</i>	
5.1	Introduction	103
5.1.1	Bioelectronic Nose Using Olfactory Receptor-Conjugated Graphene	106
5.1.2	Bioelectronics for Diagnosis Using Bioprobe-Modified Graphene	112
5.1.3	Biosensors for Environmental Component Monitoring Using Graphene	116
5.2	Conclusion	120
	Acknowledgments	120
	References	120
6	Thin-Film Transistors Based on Reduced Graphene Oxide for Biosensing	125
	<i>Kai Bao, Ye Chen, Qiyan He, and Hua Zhang</i>	
6.1	Introduction	125
6.2	Working Principle of TFT-Based Biosensing	126
6.3	TFTs Based on rGO for Biosensing	128
6.3.1	Protein Detection	128
6.3.2	Metal-Ion Detection	131
6.3.3	Nucleic Acid Detection	134
6.3.4	Small Biomolecular Biosensor	135
6.3.5	Living-Cell Biosensor	137
6.3.6	Gas Detection	138
6.4	Conclusion	140
	References	142
7	Towards Graphene-FET Health Sensors: Hardware and Implementation Considerations	149
	<i>Nicholas V. Apollo and Hualin Zhan</i>	
7.1	Introduction to Health Sensing	149
7.2	Graphene-FET in Liquid for Sensing	151
7.2.1	Graphene Transistors	153
7.2.2	Graphene Hall Structures in Liquid	156
7.2.3	Graphene Membrane Transistors	159
7.3	Device Implementation Considerations	160

7.3.1	Hardware and Instrumentation	160
7.3.2	Biostability and Biocompatibility	162
7.3.3	Medical Imaging Compatibility	163
	References	164
8	Quadratic Fit Analysis of the Nonlinear Transconductance of Disordered Bilayer Graphene Field-Effect Biosensors Functionalized with Pyrene Derivatives	169
	<i>Sung Oh Woo, Sakurako Tani, and Yongki Choi</i>	
8.1	Introduction	169
8.2	Fabrication of Graphene-Based Field-Effect Biosensors	170
8.3	Fundamental Sensing Parameters of Graphene-Based Field-Effect Biosensors	173
8.4	Disordered Bilayer Graphene Field-Effect Biosensors Functionalized with Pyrene Derivatives	174
8.5	Quadratic Fit Analysis of the Nonlinear Transconductance of Disordered Bilayer Graphene Field-Effect Biosensors	177
8.6	Conclusion	181
	Acknowledgment	181
	References	182
9	Theoretical and Experimental Characterization of Molecular Self-Assembly on Graphene Films	185
	<i>Kishan Thodkar, Pierre Cazade, and Damien Thompson</i>	
9.1	Introduction	185
9.2	Experimental Tools to Characterize Molecular Functionalization of Graphene	186
9.2.1	Considering the Three Distinct Techniques Available for Functionalizing Graphene Are the Outcomes of the Three Functionalization Techniques Consistent, Similar, Reproducible Across all Three Techniques?	187
9.2.2	What Tools and Methods Are Available to Perform Such a Characterization of Molecular Self-Assembly Across the Nano to Macro Scale?	188
9.3	Atomistic Insights to Guide Molecular Functionalization of Graphene	196
	References	203
10	The Holy Grail of Surface Chemistry of CVD Graphene: Effect on Sensing of cTNI as Model Analyte	207
	<i>Adrien Hugo, Teresa Rodrigues, Marie-Helen Polte, Yann R. Leroux, Rabah Boukherroub, Wolfgang Knoll, and Sabine Szunerits</i>	
10.1	Introduction	207

10.2	General Overview of CVD Graphene Production, Substrate Transfer and Characterization	210
10.3	Evaluation of Graphene Topographical Quality	212
10.4	CVD Graphene for FET-Based Sensing	214
10.4.1	Diazonium Chemistry on CVD Graphene	217
10.4.2	Pyrene Chemistry on CVD Graphene	220
10.5	Conclusion	225
	References	226
11	Sensing Mechanisms in Graphene Field-Effect Transistors Operating in Liquid	231
	<i>Tilmann J. Neubert and Kannan Balasubramanian</i>	231
11.1	Introduction	231
11.2	Field-Effect Operation in Liquid Compared to Operation in Air	232
11.3	Caveats When Operating FETs in Liquid	234
11.4	Graphene FETs in Liquid	235
11.5	Measurement Modes	236
11.6	Using FETs for Sensing in Liquid – Sensing Mechanisms	238
11.7	The Electrochemical Perspective	241
11.8	The GLI and pH Sensing	245
11.9	Detection of Nucleic Acids	246
11.10	Other Examples	247
11.11	Concluding Remarks	248
	References	248
12	Surface Modification Strategies to Increase the Sensing Length in Electrolyte-Gated Graphene Field-Effect Transistors	251
	<i>Juliana Scotto, Wolfgang Knoll, Waldemar A. Marmisollé, and Omar Azzaroni</i>	
12.1	Introduction	251
12.2	Ion-Exclusion and Donnan Potential	253
12.3	Surface Modification with Polymer Films	255
12.4	Surface Modification with Lipid Layers	258
12.5	Surface Modification with Mesoporous Materials	260
12.6	Kinetic Cost of Extending the Sensing Length	262
12.7	Conclusions	265
	References	266
13	Hybridized Graphene Field-Effect Transistors for Gas Sensing Applications	271
	<i>Radha Bhardwaj and Arnab Hazra</i>	271
13.1	Introduction	271
13.2	Graphene	272

13.3	Graphene FET	272
13.4	Graphene in Gas Sensing	274
13.5	Graphene FET for Gas Sensing	275
13.6	Hybrid Graphene FET for Gas Sensing	277
13.7	Conclusion	281
	Acknowledgments	281
	References	281
14	Polyelectrolyte-Enzyme Assemblies Integrated into Graphene Field-Effect Transistors for Biosensing Applications	285
	<i>Esteban Piccinini, Gonzalo E. Fenoy, Wolfgang Knoll, Waldemar A. Marmisollé, and Omar Azzaroni</i>	
14.1	Introduction	285
14.2	Field-Effect Transistors Based on Reduced Graphene Oxide	286
14.3	Enzyme-Based GFET Sensors Fabricated via Layer-by-Layer Assembly	287
14.3.1	Layer-by-Layer (LbL) Assemblies of Polyethylenimine and Urease onto Reduced Graphene-Oxide-Based Field-Effect Transistors (rGO FETs) for the Detection of Urea	288
14.3.2	Ultrasensitive Sensing Through Enzymatic Cascade Reactions on Graphene-Based FETs	292
14.4	Conclusions	296
	References	297
15	Graphene Field-Effect Transistor Biosensor for Detection of Heart Failure-Related Biomarker in Whole Blood	301
	<i>Jiahao Li, Yongmin Lei, Zhi-Yong Zhang, and Guo-Jun Zhang</i>	
15.1	Introduction	301
15.2	Experimental Systems and Procedures	304
15.2.1	Fabrication of GFET Sensor	304
15.2.2	Decoration of Platinum Nanoparticles	304
15.2.3	Surface Functionalization	305
15.2.4	Immunodetection in Whole Blood	305
15.2.5	Electrical Measurements	305
15.3	Sensing Principle of GFET for BNP Detection	306
15.4	Device Characterization	306
15.5	Sensing Performance	308
15.5.1	Stability and Reproducibility	308
15.5.2	Selectivity	309
15.5.3	Sensitivity	309
15.6	Clinical Application Prospects	311
15.7	Advantages, Limitations, and Outlook of the FET-Based BNP Assay	311
	References	313

16	Enzymatic Biosensors Based on the Electrochemical Functionalization of Graphene Field-Effect Transistors with Conducting Polymers	317
	<i>Gonzalo E. Fenoy, Esteban Piccinini, Wolfgang Knoll, Waldemar A. Marmisollé, and Omar Azzaroni</i>	
16.1	Introduction	317
16.2	Functionalization of Graphene Transistors with Poly(3-amino-benzylamine-co-aniline) Nanofilms	318
16.3	Construction of Acetylcholine Biosensors Based on GFET Devices Functionalized with Electropolymerized Poly(3-amino-benzylamine-co-aniline) Nanofilms	322
16.4	Glucose Detection by Graphene Field-Effect Transistors Functionalized with Electropolymerized Poly(3-amino-benzylamine-co-aniline) Nanofilms	327
16.5	Conclusions	332
	References	333
17	Graphene Field-Effect Transistors for Sensing Stress and Fatigue Biomarkers	339
	<i>Biddut K. Sarker, Cheri M. Hampton, and Lawrence F. Drummy</i>	
17.1	Introduction	339
17.2	Molecular Biomarkers	341
17.3	Graphene Field-Effect Transistor Based Biosensors	343
17.3.1	Graphene	343
17.3.2	Structure of Graphene Field-Effect Transistors	345
17.3.3	Sensing Mechanism of GFET Biosensors	346
17.4	GFET Biosensor Fabrication	348
17.4.1	Graphene Production	348
17.4.2	Device Fabrication	349
17.4.3	Graphene Functionalization	350
17.5	GFET-Based Stress and Fatigue Biosensors	353
17.6	Flexible, Wearable GFET Biosensors, and Biosensor Systems	358
17.7	Current Challenges and Future Perspective	362
17.7.1	Debye Length Screening	362
17.7.2	Device-to-Device Variability	366
17.7.3	Short Lifetime and Reusability Issue	366
17.8	Conclusion	367
	References	367
18	Highly Sensitive Pathogen Detection by Graphene Field-Effect Transistor Biosensors Toward Point-of-Care-Testing	373
	<i>Shota Ushiba, Takao Ono, Yasushi Kanai, Naruto Miyakawa, Shinsuke Tani, Hiroshi Ueda, Masahiko Kimura, and Kazuhiko Matsumoto</i>	
18.1	Introduction	373
18.2	Toward Detection of Pathogens by Mimicking Cell Surfaces	374

18.2.1	Introduction	374
18.2.2	Fabrication of Sialoglycan-Functionalized GFETs	375
18.2.3	Evaluation of Sialoglycan-Functionalized GFETs	375
18.3	Signal Enhancement in GFETs	377
18.3.1	Sensitivity Enhancement by Increasing Receptor Density	377
18.3.1.1	Case of Linkers	377
18.3.1.2	Basis for Evaluation of Linker-Based Performance Enhancement	378
18.3.1.3	Evaluation of Performance Enhancement by Linkers	378
18.3.2	Ultrasensitive Detection of Small Antigens by Open-Sandwich Immunoassay on GFETs	380
18.3.2.1	Principle of Open-Sandwich (OS) Immunoassay	380
18.3.2.2	Advantages of OS-IAs with GFETs	380
18.3.2.3	Antibody Fragments and Device Fabrication	381
18.3.2.4	OS-IAs on GFETs	382
18.3.2.5	OS-IAs on GFETs in Human Serum	382
18.3.3	Real-Time Measurement of Enzyme Reaction in Microdroplets Using GFETs and Its Application to Pathogen Detection	384
18.3.3.1	Introduction	384
18.3.3.2	Measurement Mechanism and Model Measurement System	385
18.4	Practical Issues: Baseline Drift and Inspection Methods	387
18.4.1	Drift Suppression and Compensation of GFET Biosensors	388
18.4.1.1	Drift Suppression in GFETs by Cation Doping	388
18.4.1.2	Drift Compensation by State-Space Modeling	390
18.4.2	Deep-Learning-Based Optical Inspection of GFETs	393
18.5	Conclusion	398
	References	398
19	High-Performance Detection of Extracellular Vesicles Using Graphene Field-Effect Transistor Biosensor	405
	<i>Ding Wu, Yi Yu, Zhi-Yong Zhang, and Guo-Jun Zhang</i>	
19.1	What is Extracellular Vesicles	405
19.2	The Clinical Significance of Extracellular Vesicles	406
19.3	Introduction to Graphene Field-Effect Transistor Biosensor	406
19.4	GFET Biosensor for High-Performance Detection of Extracellular Vesicles	407
19.4.1	Detection of the Overall Level of Microvesicles Using GFET Biosensor	408
19.4.2	Specific Detection of Hepatocellular Carcinoma-Derived Microvesicles Using Dual-Aptamer Modified GFET Biosensor	409
19.4.3	Label-Free Detection of Cancerous Exosomes Using GFET Biosensor	410
19.5	Some Prospects for Graphene Field-Effect Transistor Biosensor	411
	References	412
	Index	417