

Contents

Oxide Films and Conduction AFM *xi*

List of Contributors *xv*

1	History and Status of the CAFM	<i>1</i>
	<i>Chengbin Pan, Yuanyuan Shi, Fei Hui, Enric Grustan-Gutierrez, and Mario Lanza</i>	
1.1	The Atomic Force Microscope	<i>1</i>
1.2	The Conductive Atomic Force Microscope	<i>4</i>
1.3	History and Status of the CAFM	<i>9</i>
1.4	Editor's Choice: On the Use of CAFM to Study Nanogenerators Based on Nanowires	<i>16</i>
1.5	Conclusions	<i>20</i>
	References	<i>20</i>
2	Fabrication and Reliability of Conductive AFM Probes	<i>29</i>
	<i>Oliver Krause</i>	
2.1	Introduction	<i>29</i>
2.2	Manufacturing of Conductive AFM Probes	<i>30</i>
2.2.1	Thin Film Cantilever	<i>30</i>
2.2.2	Corner Tips	<i>30</i>
2.2.3	Etched Silicon Probes	<i>31</i>
2.2.4	Coating of Probes	<i>32</i>
2.2.5	Conductive Thin Film Probes	<i>34</i>
2.2.6	Material Conversion	<i>35</i>
2.3	How to Choose Your C-AFM Tip	<i>36</i>
2.3.1	Cantilever Choice	<i>36</i>
2.3.2	Tip Material Choice	<i>36</i>
2.3.3	Resolution of C-AFM Tips	<i>37</i>
2.4	Tip Wear and Sample Damage: Applicable Forces and Currents in C-AFM	<i>38</i>
2.4.1	Tip Wear: Mechanical Wear – Varying Forces	<i>38</i>
2.4.2	Tip Wear: Mechanical Wear – Different Materials	<i>39</i>
2.4.3	Tip Wear: Electrical Wear	<i>39</i>
2.4.4	Tip Damage by Excess Voltage/High Currents	<i>40</i>
2.4.5	Damaging the Sample Surface	<i>42</i>

2.5	Conclusions	43
	References	43
3	Fundamentals of CAFM Operation Modes	45
	<i>Guenther Benstetter, Alexander Hofer, Donping Liu, Werner Frammelsberger, and Mario Lanza</i>	
3.1	Introduction	45
3.2	Tip-Sample Interaction: Contact Area, Effective Emission Area, and Conduction Mechanisms	47
3.2.1	CAFM Tip on Metallic Surfaces	49
3.2.2	CAFM Tip on Semiconducting Surfaces	50
3.2.3	CAFM Tip on Insulating Surfaces	52
3.3	Work Function Difference and Offset Voltage	56
3.4	Operation Modes	60
3.4.1	Contact Mode	61
3.4.2	PeakForce Mode	62
3.4.3	Torsional Resonance Mode	63
3.5	Case Studies	64
3.5.1	Defects in SiC after Plasma Exposure in Fusion Reactors	64
3.5.2	Electrical Conductivity of Dislocations in GaN	67
3.5.3	Microstructure and Local Electrical Conductivity of Laser-Sintered Nanoparticles	69
3.6	Conclusion and Future Perspectives	70
	Acknowledgment	70
	References	71
4	Investigation of High-k Dielectric Stacks by C-AFM: Advantages, Limitations, and Possible Applications	79
	<i>Mathias Rommel and Albena Paskaleva</i>	
4.1	Introduction	79
4.2	Comparison Between Macroscopic $I-V$ Measurements and C-AFM	81
4.3	Influence of Displacement Currents on the Sensitivity of C-AFM Measurements	85
4.4	Applications of C-AFM	89
4.4.1	Morphology of Thin Dielectric Films	89
4.4.2	Assessment of the Interfacial SiO_2 Thickness	94
4.4.3	Trapping Phenomena and Degradation Mechanism in High- k Dielectric Stacks	98
4.4.4	Reliability of High- k Dielectric Films	104
4.4.4.1	Gate Oxide Reliability at the Nanoscale	104
4.4.4.2	In-Depth Analysis of Bimodal TDDB Distributions	109
4.5	Conclusion	112
	References	113

5	Characterization of Grain Boundaries in Polycrystalline HfO₂ Dielectrics	119
	<i>Shubhakar Kalya, Sean Joseph O'Shea, and Kin Leong Pey</i>	
5.1	Introduction	119
5.2	Experimental Details and Sample Specifications	120
5.3	Formation of Grain Boundaries and Its Local Electrical Properties in HfO ₂ Dielectric	120
5.4	RVS and CVS Stressing of HfO ₂ /SiO _x Dielectric Stack	124
5.5	Uniform Stressing with Successive Scanning in CAFM Mode	126
5.6	Conclusions	130
	References	130
6	CAFM Studies on Individual GeSi Quantum Dots and Quantum Rings	133
	<i>Rong Wu, Shengli Zhang, Yi Lv, Fei Xue, Yifei Zhang, and Xinju Yang</i>	
6.1	Introduction	133
6.2	Conductive Properties of Individual GeSi QDs and QRs	134
6.2.1	Conductive Property Studies on Individual GeSi QDs	135
6.2.1.1	Growth Temperature Dependence	135
6.2.1.2	Electrical Property Changing with the Capping of Si Layer	137
6.2.2	The Conductive Mechanism of GeSi QRs	140
6.3	Modulating the Conductive Properties of GeSi QDs	144
6.3.1	Oxidation and Normal Force	144
6.3.2	Bias Voltage	146
6.3.3	Inter-Dot Coupling	149
6.4	Simultaneous Measurements of Composition and Current Distributions of GeSi QRs	152
6.5	Conclusions	157
	References	157
7	Conductive Atomic Force Microscopy of Two-Dimensional Electron Systems: From AlGaN/GaN Heterostructures to Graphene and MoS₂	163
	<i>Filippo Giannazzo, Gabriele Fisichella, Giuseppe Greco, Patrick Fiorenza, and Fabrizio Roccaforte</i>	
7.1	Introduction	163
7.2	Nanoscale Electrical Characterization of AlGaN/GaN Heterostructures	164
7.2.1	Contacts to AlGaN/GaN Heterostructures	165
7.2.2	Electrical Nanocharacterization of AlGaN Surface Passivated by a Rapid Thermal Oxidation	168
7.2.3	CAFM on Dielectrics for Gate Insulated AlGaN/GaN Transistors	169
7.3	CAFM Characterization of Graphene and MoS ₂	171
7.3.1	Local Electrical Properties of Graphene 2DEG	173

7.3.2	Nanoscale Inhomogeneity of the Schottky Barrier and Resistivity in MoS ₂	175
7.3.3	Graphene Contacts to AlGaN/GaN Heterostructures	178
7.4	Conclusions	181
	Acknowledgments	182
	References	182
8	Nanoscale Three-Dimensional Characterization with Scalpel SPM	187
	<i>Umberto Celano and Wilfried Vandervorst</i>	
8.1	Introduction	187
8.2	SPM Metrology with Depth Information	188
8.3	Scalpel SPM: A Tip-Based Slice-and-View Methodology	190
8.3.1	General Description	190
8.3.2	Practical Implementation	193
8.4	Applications	196
8.4.1	Scalpel SPM for 3D Observation of Conductive Filaments in Resistive Memories	196
8.4.2	Mechanisms for Filament Growth	200
8.4.3	Chemical Nature of the Filament	202
8.4.4	Scalpel SPM for Failure Analysis	203
8.5	Conclusions and Outlook	206
	References	207
9	Conductive Atomic Force Microscopy for Nanolithography Based on Local Anodic Oxidation	211
	<i>Matteo Lorenzoni and Francesc Pérez-Murano</i>	
9.1	Introduction to AFM Nanolithography	211
9.2	Local Anodic Oxidation	212
9.3	Kinetics of LAO	214
9.4	Measurement of Electrical Current During LAO	217
9.5	Conclusions	219
	Acknowledgments	219
	References	220
10	Combination of Semiconductor Parameter Analyzer and Conductive Atomic Force Microscope for Advanced Nanoelectronic Characterization	225
	<i>Vanessa Iglesias, Xu Jing, and Mario Lanza</i>	
10.1	Introduction	225
10.2	Combination of SPA and CAFM for Local Channel Hot Carrier Degradation Analysis	227
10.3	Combination of CAFM and SPA for Resistive Switching Analyses	230
10.3.1	Device-Level Stress with SPA Followed by CAFM Characterization	230
10.3.2	Direct Connection of SPA to the CAFM	235

10.4	Conclusions	237
	References	238
11	Design and Fabrication of a Logarithmic Amplifier for Scanning Probe Microscopes to Allow Wide-Range Current Measurements	243
	<i>Lidia Aguilera and Joan Grifoll-Soriano</i>	
11.1	Introduction	243
11.2	Fabrication of a Logarithmic Preamplifier for CAFMS	244
11.2.1	Design	244
11.2.2	Fabrication and Testing	249
11.2.2.1	Printed Circuit Board	249
11.2.2.2	Cleaning	250
11.2.2.3	Decoupling	250
11.2.2.4	Input and Output Isolation	251
11.2.2.5	Unexpected Passive Components in the PCB	251
11.2.3	Implementation in a CAFM and Case Study	255
11.3	Conclusions	260
	References	261
12	Enhanced Current Dynamic Range Using ResiScope™ and Soft-ResiScope AFM Modes	263
	<i>Louis Pacheco and Nicolas F. Martinez</i>	
12.1	Introduction	263
12.2	Conductive AFM	264
12.3	ResiScope™ Mode	267
12.4	Soft-ResiScope Mode	271
12.5	Conclusions	275
	References	275
13	Multiprobe Electrical Measurements without Optical Interference	277
	<i>David Lewis, Andrey Ignatov, Sasha Krol, Rimma Dekhter, and Alina Strinkovsky</i>	
13.1	Introduction	277
13.2	The Multiprobe Platform: Design and Key Features	279
13.2.1	The Scanner	279
13.2.2	The Probes	281
13.2.3	Feedback of Multiprobe Systems	282
13.3	The Present and the Future	284
13.3.1	AFM Multiprobe Application	284
13.3.2	Optical Multiprobe Operation	285
13.3.3	Thermal Measurements	285
13.3.4	NanoElectrical Transport Measurements	287
13.3.5	New Horizons in Multiprobe Measurements	291
13.4	Conclusions	292
	References	293

14	KPFM and its Use to Characterize the CPD in Different Materials	297
	<i>Yijun Xia and Bo Song</i>	
14.1	Introduction	297
14.2	Kelvin Probe Force Microscopy	297
14.2.1	Basic Principle of Kelvin Probe Force Microscopy	297
14.2.2	KPFM Operational Modes: AM- and FM-Mode	299
14.2.3	KPFM Measurement, at Ambient or UHV Conditions	300
14.3	Applications of KPFM	301
14.3.1	KPFM on Conventional Inorganic Materials	301
14.3.1.1	Metallic Nanostructures	301
14.3.1.2	Semiconductor Surfaces	302
14.3.2	KPFM on Organic Adsorbates on Surfaces	304
14.3.3	Characterization of the Electrical Properties of Nanoscaled Devices	305
14.3.3.1	Junctions and Heterostructures	305
14.3.3.2	Transistors	307
14.3.3.3	Solar Cells	308
14.4	Conclusion and Outlook	311
	Acknowledgment	312
	References	312
15	Hot Electron Nanoscopy and Spectroscopy (HENs)	319
	<i>Andrea Giugni, Bruno Torre, Marco Allione, Gerardo Perozziello, Patrizio Candeloro, and Enzo Di Fabrizio</i>	
15.1	Introduction	319
15.2	Coupling Schemes	321
15.3	Plasmonic Device and Optical Characterization	326
15.4	Theoretical Section	327
15.4.1	Semiclassical Considerations	329
15.4.2	Quantum Mechanical Considerations	333
15.4.3	Quantum Confinement	334
15.5	HENs Measurements: Plasmon-Assisted Current Maps and Ultimate Spatial Resolution	335
15.5.1	Hot Electron Mapping	336
15.5.2	Hot Electron Resolution Limit	338
15.6	Kelvin Probe, HENs, and Electrical Techniques	340
15.6.1	SKPM Theoretical Frame: a Short Introduction	340
15.6.2	HENs	344
15.6.2.1	Spatial Resolution	344
15.6.2.2	Sensitivity and Specificity	344
15.7	Fast Pulses in Adiabatic Compression for Hot Electron Generation	347
15.8	Conclusion	348
	Acknowledgments	349
	References	349
	Index	355