

H.-J. Güntherodt R. Wiesendanger (Eds.)

Scanning Tunneling Microscopy I

General Principles and Applications
to Clean and Adsorbate-Covered Surfaces

Second Edition

With Contributions by

D. Anselmetti R. J. Behm

P. J. M. van Bentum S. Chiang H.-J. Güntherodt

R. J. Hamers H. J. Hug H. van Kempen Y. Kuk

H. Rohrer R. Wiesendanger J. Winterlin

With 172 Figures

Springer-Verlag

Berlin Heidelberg New York

London Paris Tokyo

Hong Kong Barcelona

Budapest

Contents

1. Introduction

By <i>R. Wiesendanger</i> and <i>H.-J. Güntherodt</i> (With 5 Figures)	1
1.1 Historical Remarks on Electron Tunneling	1
1.2 STM and Related Techniques	4
1.2.1 Local Proximal Probes	4
1.2.2 Modes of Operation	5
1.3 Development of the Field	8
1.4 Prospects for the Future	9
References	11

2. The Rise of Local Probe Methods

By <i>H. Rohrer</i>	13
-------------------------------	----

3. STM on Metals

By <i>Y. Kuk</i> (With 19 Figures)	17
3.1 Tunneling Tip	18
3.2 Tunneling Spectroscopies	20
3.2.1 Current Versus Gap Distance	20
3.2.2 Electronic Structure by dI/dV	22
3.3 Examples on Metal Surfaces	25
3.3.1 Surface Structures	25
3.3.2 Dynamics	30
3.4 Conclusion	35
References	35

4. Adsorbate Covered Metal Surfaces and Reactions on Metal Surfaces

By <i>J. Winterlin</i> and <i>R.J. Behm</i> (With 22 Figures)	39
4.1 Imaging of Adsorbates by STM	40
4.1.1 Representation of Individual Adsorbates	40
4.1.2 Resolution and Corrugation in Closed Adlayers	47
4.1.3 Spectroscopy of Adsorbates	50
4.2 Processes at the Metal–Gas Interface	54
4.2.1 Adsorption, Dissociation, Surface Diffusion	54
4.2.2 Formation of Ordered Adsorbate Layers	58
4.3 Structure Modifications of Metal Surfaces	60
4.3.1 Adsorbate-Induced Reconstructive Transformations	60
4.3.2 Oxidation Reactions	68

4.4 Epitaxial Growth of Metals on Metal Substrates	70
4.5 Conclusions	79
References	79
5. STM on Semiconductors	
By <i>R.J. Hamers</i> (With 29 Figures)	83
5.1 Experimental Technique	83
5.1.1 Topographic Imaging	83
5.1.2 Tunneling Spectroscopy	85
5.2 Scanning Tunneling Microscopy/Spectroscopy on Surfaces . .	87
5.2.1 Clean Group IV Semiconductors	87
5.2.2 Clean Compound Semiconductor Surfaces	106
5.2.3 Adsorbates and Overlayers on Semiconductors	113
5.2.4 Chemical Reactions on Semiconductor Surfaces	119
5.3 Other Tunneling Techniques Applied to Semiconductors	120
5.3.1 Surface Photovoltage	120
5.3.2 Tunneling-Induced Luminescence	123
5.3.3 Potentiometry	124
5.3.4 Ballistic Electron Emission Microscopy (BEEM)	125
References	126
6. STM on Layered Materials	
By <i>R. Wiesendanger</i> and <i>D. Anselmetti</i> (With 44 Figures)	131
6.1 STM Studies of Graphite	132
6.1.1 Site Asymmetry, Energy-Dependent Corrugation, Tunneling Spectroscopy and Electronic Structure of the Graphite Surface	133
6.1.2 Giant Corrugations, Tip-Sample Interaction and Elastic Response of the Graphite Surface	136
6.1.3 Anomalous STM Images	138
6.1.4 STM Imaging of Defects	140
6.1.5 STM Studies of Clusters on the Graphite Surface	142
6.2 STM Studies of Graphite Intercalation Compounds	145
6.2.1 Donor Graphite Intercalation Compounds	149
6.2.2 Acceptor Graphite Intercalation Compounds	154
6.2.3 Interpretation and Comparison with Theoretical Predictions	154
6.3 STM Studies of Transition Metal Dichalcogenides	157
6.4 STM Studies of Charge Density Waves	161
6.4.1 Charge Density Waves in Transition Metal Dichalcogenides	161
6.4.2 Charge Density Wave Defects and Domains	165
6.4.3 Charge Density Waves in Quasi-One-Dimensional Systems	170
6.5 STM Studies of High- T_c Superconductors	172

6.6 Concluding Comments	175
References	175
7. Molecular Imaging by STM	
By <i>S. Chiang</i> (With 19 Figures)	181
7.1 Introduction to STM of Molecules	181
7.2 STM of Chemisorbed Molecules in Ultrahigh Vacuum.....	182
7.2.1 Coadsorbed Benzene and CO on Rh(111)	182
7.2.2 Copper-Phthalocyanine on Cu(100) and GaAs (110) ...	186
7.2.3 Naphthalene on Pt(111)	188
7.3 STM of Alkanes and Their Derivatives	191
7.3.1 Cadmium Arachidate and Other Langmuir–Blodgett Films	191
7.3.2 <i>n</i> -Alkanes on Graphite	194
7.3.3 Alkylbenzenes on Graphite	195
7.4 STM of Liquid Crystals	197
7.4.1 Alkylcyanobiphenyls	197
7.4.2 Other Liquid Crystals	199
7.5 STM of Polymers	200
7.5.1 PODA, PMMA, and PMPS on Graphite	200
7.5.2 Polyethylene on Graphite	202
7.6 Other Molecules	202
7.7 Conclusions	203
References	203
8. STM on Superconductors	
By <i>P.J.M. van Bentum</i> and <i>H. van Kempen</i> (With 21 Figures)....	207
8.1 Theory of Tunneling into Superconductors	208
8.1.1 Coulomb Blockade	214
8.2 Low Temperature STM Spectroscopy on Classical Superconductors	215
8.3 Vortices	216
8.4 Organic Superconductors	220
8.5 STM Topography on High- T_c Superconductors	221
8.5.1 Granularity and Growth Structures	221
8.5.2 Potentiometry	223
8.5.3 Incommensurate Modulation	224
8.6 STM Spectroscopy on High- T_c Superconductors	226
8.6.1 Normal State Spectroscopy	226
8.6.2 STM Spectroscopy of the Superconducting State	229
8.6.3 Energy Gap	230
8.7 Concluding Remarks	238
References	239
Subject Index	243

9. Recent DevelopmentsBy *Y. Kuk, J. Wintterlin, R. J. Behm, S. Chiang,**H.-J. Güntherodt, H. J. Hug* (With 13 Figures) 243

9.1 STM on Metal Surfaces 243

9.2 Adsorption on Metal Surfaces 245

9.2.1 Dynamics of Surface Processes 245

9.2.2 Adsorbate Structures 248

9.2.3 Adsorbate-Induced Reconstructions 248

9.2.4 Phase Transitions 252

9.2.5 Metal-on-Metal Epitaxy 253

9.3 Molecular Imaging by STM 258

9.3.1 STM of Molecules on Metals in Ultrahigh Vacuum .. 258

9.3.2 Naphthalene, Azulene and Methylazulenes on Pt(111) 259

9.3.3 Benzene on Pt(111) 262

9.3.4 Ethylene on Pt(111) 262

9.3.5 C₆₀ on Au(111) and Cu(111) 265

9.3.6 Conclusions 267

9.4 STM on Superconductors 268

9.4.1 STM on Conventional Superconductors 268

9.4.2 STM on High-T_c Superconductors 2699.4.3 Scanning Probe Microscopy on High-T_c
Superconductors 269

References 269

Subject Index 277