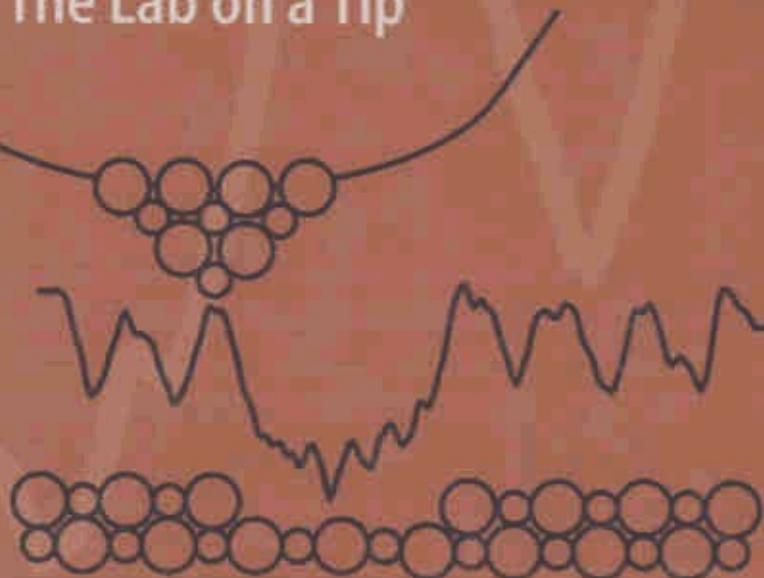


Ernst Meyer
Hans Josef Hug
Roland Bennewitz

Scanning Probe Microscopy

The Lab on a Tip



Springer

Contents

1	Introduction to Scanning Probe Microscopy	1
1.1	Overview	2
1.2	Basic Concepts	5
1.2.1	Local Probes	6
1.2.2	Scanning and Control	7
1.2.3	Vibrational Isolation	11
1.2.4	Computer Control and Image Processing	12
2	Introduction to Scanning Tunneling Microscopy	15
2.1	Tunneling: A Quantum-Mechanical Effect	16
2.1.1	Tersoff-Hamann Model	18
2.2	Instrumental Aspects	19
2.2.1	Tunneling Tips	19
2.2.2	Implementation in Different Environments	21
2.2.3	Operation Modes	21
2.2.4	Manipulation Modes	26
2.3	Resolution Limits	29
2.3.1	Imaging of Semiconductors	29
2.3.2	Imaging of Metals	30
2.3.3	Imaging of Layered Materials	31
2.3.4	Imaging of Molecules	32
2.3.5	Imaging of Insulators	33
2.3.6	Theoretical Estimates of Resolution Limits	33
2.4	Observation of Confined Electrons	34
2.4.1	Scattering of Surface State Electrons at Steps	34
2.4.2	Scattering of Surface State Electrons at Point Defects	36
2.4.3	Electron Confinement to Nanoscale Boxes	37
2.4.4	Summary of Dispersion Relations for Noble-Metal (111) Surfaces	40
2.5	Spin-Polarized Tunneling	41
2.6	Observation of the Kondo Effect and Quantum Mirage	44

VIII Contents

3 Force Microscopy	45
3.1 Concept and Instrumental Aspects	45
3.1.1 Deflection Sensors: Techniques to Measure Small Cantilever Deflections	45
3.1.2 Spring Constants of Rectangular Cantilevers	46
3.1.3 Cantilever and Tip Preparation	49
3.1.4 Implementations of Force Microscopy	50
3.2 Relevant Forces	51
3.2.1 Short-Range Forces	51
3.2.2 Van der Waals Forces	52
3.2.3 Electrostatic Forces	53
3.2.4 Magnetic Forces	55
3.2.5 Capillary Forces	56
3.2.6 Forces in Liquids	57
3.3 Operation Modes in Force Microscopy	58
3.4 Contact Force Microscopy	61
3.4.1 Topographic Imaging	61
3.4.2 Lateral Resolution and Contact Area	64
3.4.3 Friction Force Microscopy	65
3.4.4 Atomic Friction Processes	67
3.4.5 Lateral Contact Stiffness	70
3.4.6 Velocity Dependence of Atomic Friction	72
3.5 Dynamic Force Microscopy	73
3.5.1 Modelling Dynamic Force Microscopy	74
3.5.2 High-Resolution Imaging	76
3.5.3 Spectroscopic Measurements	78
3.5.4 Kelvin Probe Microscopy	79
3.5.5 Dissipation Force Microscopy	81
3.6 Tapping Mode Force Microscopy	87
3.6.1 Principles of Operation	87
3.6.2 Phase Imaging	88
3.6.3 Non-Linear Effects	89
3.7 Further Modes of Force Microscopy	90
3.8 Force Resolution and Thermal Noise	92
4 MFM and Related Techniques	97
4.1 MFM Operation Modes	98
4.1.1 Tip-Sample Distance Control	98
4.1.2 Measurement of Magnetic Forces	101
4.2 Contrast Formation	102
4.2.1 Introduction	102
4.2.2 Stray Fields of Simple Micromagnetic Structures	104

4.2.3	Negligible Modifications	108
4.2.4	Reversible Modifications	115
4.2.5	Irreversible Modifications	119
4.2.6	Separation of Topography and Magnetic Signal	121
4.3	Magnetic Resonance Force Microscopy	124
5	Other Members of the SPM Family	127
5.1	Scanning Near-Field Optical Microscopy (SNOM)	127
5.2	Scanning Near-Field Acoustic Microscopy (SNAM)	132
5.3	Scanning Ion Conductance Microscopy (SICM)	133
5.4	Photoemission Microscopy with Scanning Aperture (PEMSA) .	135
5.5	STM with Inverse Photoemission (STMiP)	135
5.6	Laser Scanning Tunneling Microscopy (LSTM)	136
5.7	Electrochemical Scanning Tunneling Microscopy (ECSTM) .	137
5.8	Scanning Thermal Microscopy (SThM)	139
5.9	Scanning Noise Microscopy (SNM)	141
5.10	Scanning Tunneling Potentiometry (SPotM)	142
5.11	Scanning Capacitance Microscopy (SCM)	142
5.12	Scanning Spreading Resistance Microscopy (SSRM)	146
5.13	Scanning Tunneling Atom Probe (STAP)	150
6	Artifacts in SPM	153
6.1	Tip Artifact: Convolution with Tip Shape	153
6.2	Influence of Local Inhomogeneities on Topography	160
6.2.1	STM Topography	160
6.2.2	SFM Topography	161
6.3	Influence of Topography on Local Measurements	163
6.3.1	STM-Induced Photon Emission	164
6.3.2	Lateral Force Measurement	165
6.4	Instrumental Artifacts	167
6.4.1	Piezoelectric Hysteresis, Scanner Creep, Non-Linearities and Calibration Errors	167
6.4.2	Tip Crashes, Feedback Oscillations, Noise, Thermal drift	169
6.4.3	Interference Patterns with Beam Deflection SFM	170
7	Prospects for SPM	173
7.1	Parallel Operation of SFM Cantilever Arrays	173
7.2	Novel Sensors Based on Cantilevers	175
7.2.1	Gravimetric Sensors	176
7.2.2	Calorimeter Sensors	176
7.2.3	Surface Stress Sensors	176
7.2.4	Cantilever Array Sensors	177

X **Contents**

7.3 Molecular Electronics	178
7.4 Laboratory on a Tip	179
7.5 Local Modification Experiments	179
References	181
Index	207