а

acoustic excitation 91 acoustic method practical considerations 135 - 137acoustic radiation pressure method 130 β -actin mRNA 334, 335 active damping techniques 196-198 adhesion 211, 212-213, 216, 217, 218, 219, 221, 223, 225, 307, 308, 310, 312, 315, 318, 323 adhesion bonds dynamics 165 - dissociation dynamics - - in force clamp and need for robust statistics 168-169 -- in length clamp 165-167 - general considerations 167-168 air-liquid interface during approach 54-55 air-liquid interface during withdrawal 58 Alberts-Meselson-Sigal (AMS) model 245 alkyl chains, choice of 201 aminopropyltriethoxy silane (APTES) 235 amplitude-modulation atomic force microscopy (AM-AFM) 19, 22, 88-89, 93-97, 111, 136, 147 Aspergillus fumigatus 289 atomic force microscope 65-66, 73, 77, 81, see also individual entries - artifacts related to tip geometry 28-29 - - artifacts related to feedback loop 30 – resolution limits 31–32 - components of 4 - feedback loop 24-25 - force detection methods 15 – laser beam deflection method 17–19 – piezoelectric cantilever method 15 - 16-- tuning fork method 16-17

- image representation 25-28 - operation modes 19 -- contact mode 19-20 -- dynamic modes 22-24 – jumping and pulsed force mode 20 - 22piezolelectric scanners 5-8 - - for imaging in liquids 8 - principles 3-4 tips and cantilevers 8–10 - – calibration 10–11 – dynamics in liquids 13–15 – for imaging in liquids 11–13 atomic-scale contact/noncontact regime 94

b

bacteriorhodopsin – crystal edge 203–204 - photoactivation of 204-206 Bell-Evans theory 323 BFP, see biomembrane force probe bimorph bending effect 138 biological findings using AFM-SMFS 177 folding process monitoring by force-clamp spectroscopy 180 - intermolecular binding forces and energies 180 - 181- new insights at single-molecule level 181 - titin 177-180 biological systems, solvation forces in 106 - 108biomembrane force probe (BFP) 308 biomolecular assemblies 113-114 biomolecules, unfolding and stretching of 108-110 bond rupture 323, 325 breakthrough force as molecular fingerprint 263-265

Atomic Force Microscopy in Liquid: Biological Applications, First Edition. Edited by Arturo M. Baró and Ronald G. Reifenberger.

© 2012 Wiley-VCH Verlag GmbH & Co. KGaA. Published 2012 by Wiley-VCH Verlag GmbH & Co. KGaA.

~

С Ca²⁺ fluorescence microscopy 215 - 217CAM, see cell adhesion molecules cantilever - calibration 311 - cell attachment to AFM 311-313 - choice 310 - dynamics interacting with samples 140 - 141-- compositional mapping 145-147 – force spectroscopy implications 148-149 – oscillating probes experimental observations 141-142 – oscillating probes modeling and numerical simulations 142-145 - functionalization 310-311 - hydrodynamics 123-126 – oscillation fundamentals review 122–123 - and tips 8-10 -- dynamics in liquids 13-15 -- calibration 10-11 – – for imaging in liquids 11–13 carbon nanotube (CNT) 35 - AFM tips performance 58-59 - biological imaging in liquid medium with AFM tips 59-60 - cell membrane penetration and intracellular AFM probes applications 60-61 - chemical functionalization 44-45 -- of free end 45 -- sidewall coating 45-46 - mechanical properties in relation to AFM applications 46-47 -- atomic structure 47-49 – CNT AFM tips mechanical properties 49 - 50- needles application 344-346 - probe fabrication 37-38 – mechanical attachment 38–39 - attachment techniques which employ magnetic and electric fields 39, 41 - - coating with metal and tip 44 -- direct growth of tips 41-43 – emerging attachment techniques 43 - - shortening and tip length 43-44 - tips dynamics in liquids 50 - - AFM tips in liquids 52 - - interaction with liquids 52, 54-58 - - microfabricated AFM tips and cantilevers interaction in liquids 50-52 catch bonds 325 cell adhesion molecules (CAMs) 307, 320

cell adhesion quantification by single-cell force spectroscopy 317-319 cell and tissue local stiffness/elasticity measurement 213 cell-cell adhesion measurement 325-326 cell mechanical forces measurement and application 213 cell topography 212 cellular endoscope 346 cellular sensors 285 - AFM detection of single sensors 290-291 - - bringing yeast sensor to surface 291-292 - atomic force microscopy of live cells 288-289 - mechanosensors in living cells 285-286 probe of single yeast sensors in live cells - - imaging sensor clustering 295-298 - - sensor spring properties measurement 292-295 – use of sensors as molecular rulers 298-302 - yeast cell wall integrity sensors 286-288 cell wall integrity (CWI) 286-288, 287, 288, 291, 296, 303 chemical force microscopy (CFM) 44, 81 Chinese hamster ovary (CHO) cells 320 chromatin dynamics time-lapse AFM 251-253 closed-loop feedback system 313-314 clustering 295-298, 296, 297, 299 coarse-grained simulations 176 compositional mapping 145-147 constant force mode 314 constant height mode 314 contact mode 3, 8, 9, 12, 19-20, 51, 87 control theory 24 Crooks fluctuation theorem 168 CWI, see cell wall integrity cysteine-rich domain (CRD) 287, 288, 292, 297, 298, 299 cytoskeleton 60, 307, 309, 318, 319, 334, 338, 339, 343, 344, 349-350

d

Debye length 74, 75 derivative filtering 27 Derjaguin approximation 72, 74, 75 Derjaguin–Landau–Verwey–Overbeek (DLVO) theory 266 – between two surfaces 71–72 diffuse electric double layer 73 digital signal processor (DSP) 4–5

dipalmitoylphosphatidylcholine (DPPC) 201 - cantilever deflection measurement dipalmitoylphosphatidylglycerol (DPPG) 201 dipalmitoylphosphatidylserine (DPPS) 201 dipalmitoylphosphoric acid (DPPA) 201 direct forcing methods 128, 129-131 dither piezoelectric/acoustic method 128, 132 DNA 174 - condensation 253-254 - delivery and gene expression 335-337 DNA and protein-DNA complexes 233 - AFM imaging of alternative DNA conformations -- cruciforms in DNA 239-243 - - four-way DNA junctions and DNA recombination 245-247 - - intramolecular triple helices 244-245 - AFM of DNA in aqueous solutions 236 -- DNA segmental mobility 237-239 - - elevated resolution in aqueous solutions 236-237 - dynamics - - chromatin dynamics time-lapse AFM 251-253 – site-specific protein–DNA complexes 247-251 - sample preparation for AFM imaging of 234-236 double tip 29 dynamic atomic force microscopy (dAFM), see dynamic mode AFM in liquid; liquid environments, AFM cantilever dynamics in dynamic excitation methods 126, 128 - acoustic method practical considerations 135 - 137 cantilever excitation methods review 128-130 - direct forcing 130-131 excitation methods comparison 133-135 - frequency modulation considerations in liquids 140 - ideal dither piezoelectric/acoustic excitation 132 - photothermal method 137-140 thermally driven vibration 132–133 dynamic force spectroscopy 321-325 dynamic mode AFM in liquid 87-88 - high-resolution imaging 110, 112 -- biomolecular assemblies 113-114 -- solid crystals 112-113 -- water distribution 114-116 instrumentation -- amplitude-AFM 93-97

- -- operating conditions 93
- operation principles 88
- - amplitude and phase modulation AFM 88-89
- -- frequency-modulation AFM 89-90
- quantitative measurements 97-98
- conservative and dissipative forces 101 - 103
- single-molecule force spectroscopy 108 - 110
- solvation force measurements 103 - 108
- spring constant calibration 98–101
- dynamic molecular process imaging 203
- bacteriorhodopsin crystal edge 203-204
- photoactivation of bacteriorhodopsin 204-206

е

elasticity 288, 292, 293, 295 electrical double layer (EDL) 66, 72, 78, 79 electric double layer 11 electron beam deposition (EBD) 193, 194 electron-beam-induced deposition (EBID) process 346 electrostatic excitation 129 electrostatic forces 66 between surfaces in liquid 72–76 electrothermal method 129 energy dissipation spectroscopy 147 epifluorescence microscopy 214-215, 217 equipartition theorem 130, 143 ethylenediamine (ED) 46 Euler-Bernoulli beam equation 130, 132, 143 excitation light source 215 excitation methods comparison 133-135 extracellular matrix (ECM) 307, 320, 344

f

fast amplitude detector 194 fast phase detector 199-200 feedback bandwidth and imaging time 190 feedback control method 196 feedback set point 20 femtosecond laser ablation method 339 filter assembly 215 fluid borne loading 137

⁹¹_92 -- cantilever excitation 90-91

fluorescein-isothiocyanate (FITC)-modified needle 335 fluorescence in situ hybridization (FISH) method 334 focal adhesion 338, see also adhesion force-clamp mode 163-164 - bond dissociation dynamics in 168-169 folding process monitoring by 180 force detection methods 15 - laser beam deflection method 17-19 - piezoelectric cantilever method 15-16 tuning fork method 16–17 force-distance curves - processing 315-316 recording 313–315 force inversion 97 force spectroscopy 65-67, 263, 266, 267, 268, 272, 275, 276, 277, 279 - DLVO forces theory between two surfaces 71 - 72- electrostatic force between surfaces in liquid 72-76 - force curves measurement 67-68 -- analysis in air 68-70 – analysis in liquid 70 - forces between macroscopic bodies 71 - hydrophobic forces 81 - imaging of single DNA molecules 78-79 - implications 148-149 - solvation forces 79-81 spatially resolved 76–77 - steric forces 81-82 - surface force measurement by surface force apparatus 70 van der Waals forces and Hamker constant 72 forest of peaks problem 23-24, 128, 135, 140 forest of resonances 23 Förster distance 221–222 frequency-modulation atomic force microscopy (FM-AFM) 19, 23, 80, 89-90, 95-96, 109, 111, 112, 113, 136, 147 frequency modulation considerations in liquids 140 FRET 221-222 - AFM 222-223 - near-field scanning microscopy (NSOM) 222 full width at half maximum (FWHM) 28, 29, 50

g

G4-DNA complexes 253 Galerkin discretization 131, 132, 143 glycophorin A 349 GroEL 113

h

Halobacterium salinarum 203 Hamker constants 72, 75 harmonics 122 highly orientated pyrolytic graphite (HOPG) 104 high-speed AFM 189-190 - active damping techniques 196-198 - dynamic molecular process imaging 203 – bacteriorhodopsin crystal edge 203–204 - - photoactivation of bacteriorhodopsin 204-206 - fast amplitude detector 194 - fast phase detector 199-200 - future prospects - - high-speed AFM combined with fluorescence microscope 206-207 - - imaging rate and low invasiveness 206 - high-speed scanner 194-196 - imaging time and feedback bandwidth 190 - parachuting suppression 198-199 - small cantilevers 192-194 - substrate surfaces 200 - - streptavidin 2D crystal surface 201-203 - - supported planar lipid bilayers 200-201 - time delays 191-192 high-speed scanner 194-196 Holliday junctions 245, 246 hydration forces 79 hydrophobic forces 81 i induced displacement methods 128-129 inorganic solids in nonpolar liquids 104-106 integrin 217, 309, 320, 325, 326 $-\alpha_v$ 344 interference reflection microscopy 217–218, 219, 220-221 - optical set up 218 intermolecular binding forces and energies in pairs of biomolecules 180-181 intermolecular single-molecule markers 174 - 176intramolecular single-molecule markers 170 - 174

j" events 318–319 jumping and pulsed force mode 20-22 jump-to-contact 87, 95

k KRISS nanoforce calibrator 101

1

Langmuir-Blodgett (LB) technique 260 laser beam deflection method 17-19 length-clamp mode 160-163, 173, 177 - bond dissociation dynamics in 165-167 ligand-receptor interactions 110 linear time-invariant (LTI) system 148 lipid bilayers 259-262 biological membranes – – cell membrane 259 - mechanical characterization 263 – AFM tip-lipid bilayer interaction 265-267 – breakthrough force as molecular fingerprint 263-265 - - chemical composition effect on mechanical stability of 267-268 – different cations effect on mechanical stability 271-273 - – ionic strength effect 268–271 - - phase-segregated case 274-278 – temperature effect on mechanical stability 273-274 lipid membranes, see lipid bilayers liposome rupture method 260 liquid cell 5 - beam deflection 18-19 - dynamic modes 23-24 liquid environments 121 - cantilever dynamics interacting with samples 140-141 -- compositional mapping 145-147 – force spectroscopy implications 148 - 149 – oscillating probes experimental observations 141-142 - - oscillating probes modeling and numerical simulations 142-145 - cantilever hydrodynamics in liquids 123-126 cantilever oscillation fundamentals review 122 - 123 – dynamic excitation methods 126, 128 – acoustic method practical considerations 135 - 137- - cantilever excitation methods review 128-130 -- direct forcing 130-131 – excitation methods comparison 133–135 – frequency modulation considerations in liquids 140

excitation 132 - - photothermal method 137-140 -- thermally driven vibration 132-133 liquid-solid interface 56 live cells - atomic force microscopy 288-289 - mechanosensors in 285-286 - probe of single yeast sensors in - - imaging sensor clustering 295-298 - - sensor spring properties measurement 292 - 295 – use of sensors as molecular rulers 298 - 302living cells nanosurgical manipulation - basic mechanical properties 331-332 - carbon nanotube needles application 344-346 - cellular adaptation to local stresses 343-344 - DNA delivery and gene expression 335-337 - fabricated AFM probes with hooking function 346-347 - - result for living cell 348 – semi-intact cell result 348 - hole formation on cell membrane 332-334 - intracellular stress fiber mechanical manipulation – AFM used as lateral force microscope 338-340 – force curves and fluorescence images under lateral force application 340-343 - mechanical manipulation 331 - membrane protein extraction 348-350 - mRNA extraction 334-335 m macroscopic bodies 71 magnetic excitation 91 magnetic method 129 mechanical clamp 171 mechanical resistance of protein 166 membrane protein extraction 348-350 membrane rafts 276 mica functionalization 235 microdomains 276-277 Monte Carlo simulations 167 mRNA extraction 334-335 multiwalled carbon nanotube (MWNT) 35, 37, 38-39, 41, 44, 47, 49-50, 52, 54-55, 57, 58-59, 60-61

– ideal dither piezoelectric/acoustic

Mycobacterium bovis 81

n

nanomechanics 274, 279, 292, 303 nanoneedle 335 nanoscalpel 346 near-field scanning microscopy (NSOM) 222 nitrilotriacetic acid (NTA) 290–291 nucleosomes 251–253

0

octamethylcyclotetrasiloxane (OMCTS) 104, 105 optical beam deflection (OBD) 88, 91, 92 – sensor 93 optical microscopy 211–214, 309 AFM and fluorescence microscopy combination 214-215 application examples – AFM–epifluorescence microscopy 217 – Ca²⁺ fluorescence microscopy 215 - 217- FRET 221-222 -- AFM 222-223 – near-field scanning microscopy (NSOM) 222 interference reflection microscopy (IRM) 217-218, 220-221 - sample preparation and experimental setup -- cantilever preparation 224 - - cell culture, transfection, and fura-loading 223 - 224 – typical experimental procedure 224-225 - total internal reflection fluorescence microscopy 218-221 overlap repulsion, see steric forces

р

parachuting suppression 198–199 passive elasticity 177 paxillin 344, 345 persistence length 170, 172 phase-locked loop (PLL) circuit 90 phase modulation AFM 88–89, 96–97 photothermal method 129, 137–140 piezoelectric cantilevers 15–16, 128 piezo hysteresis 313, 314 piezolelectric scanners 5–8 – for imaging in liquids 8 planar lipid bilayers 200–201 plane subtraction 26–27 point-mass model 122, 144, 147 Poisson–Boltzmann (PB) equation 74 polyethylene glycol (PEG) 175, 290 polyprotein strategy 172, 173 polysaccharides 174 position-sensitive photodetector (PSPD) 91, 92 proportional-integral-derivative (PID) 190, 191, 192, 198 proteins 171–172 – folding 161, 164, 171, 180, 182 – unfolding 160, 161, 162, 165, 167, 168, 169, 170, 171, 181 P-selectin 325

9

Q-control 196, 197 Q-factors 121, 123, 124, 134 quartz tuning forks 130

r

receptor–ligand adhesions on cell surface 212–213 receptor–ligand interaction 319 red blood cells (RBCs) 348, 349 red fluorescent protein (RFP) 223 retraction F–D curves 317 RNA polymerase (RNAP) 247

S

Saccharomyces cerevisiae 286, 288, 289, 292, 295, 296, 298, 303 Sader's equation 339 Sader method 98, 101, 143 sample excitation 129 scanning probe acceleration microscopy (SPAM) method 148 scanning probe microscopes (SPMs) 3 scanning tunneling microscope (STM) 3,65 scanning tunneling spectroscopy (STS) 65 self-oscillation circuit 89 semi-intact cells 334, 348 sensograms 300, 301 serine/threonine-rich (STR) region 287, 291, 293.303 set-point amplitude 51, 191, 198 single-cell force spectroscopy (SCFS) 307 cantilever -- calibration 311 - - cell attachment to AFM 311-313 -- choice 310 -- functionalization 310-311 - cell-cell adhesion measurement 325-326 - dynamic force spectroscopy 321-325

- force-distance curve

-- processing 315-316 -- recording 313-315 - quantification of cell adhesion by 317-319 - with single-molecule resolution 320 - 321single-electron transfer mechanism (SET) 181 single-molecule force spectroscopy (SMFS) 66, 157-158, 290, 292 - adhesion bonds dynamics 165 – bond dissociation dynamics in force clamp and need for robust statistics 168-169 - - force curves and fluorescence images – bond dissociation dynamics in length clamp 165-167 – general considerations 167–168 - AFM principles and 159-160 – force-clamp mode 163–164 -- length-clamp mode 160-163 - biological findings using AFM and 177 – folding process monitoring by force-clamp spectroscopy 180 - - intermolecular binding forces and energies in pairs of biomolecules 180 - 181 – new insights at single-molecule level – – titin 177–180 - biology and 158 ligand-receptor interactions 110 - specific versus other interactions 169 - 170- - intermolecular single-molecule markers 174-176 - - intramolecular single-molecule markers 170 - 174 steered molecular dynamics simulations 176 - 177- techniques and ranges 158-159 unfolding and stretching of biomolecules 108 - 110single-walled carbon nanotube (SWNT) 35, 37, 38, 41, 43, 46, 47, 50, 52, 58, 59 small cantilevers 192-194 smoothing filter 27 snap-back point 69 soft cantilevers 9, 12 solid crystals 112-113 solid supported lipid bilayers (SLBs), see lipid bilayers solvation forces 79-81 - measurements 103-104 – biological systems 106–108 - - inorganic solids in nonpolar liquids 104-106

– – pure water 106 Staphylococcus aureus bacteria cells 145 steered molecular dynamics simulations 176 - 177steric forces 81-82 steric stabilization 81 stiff cantilevers 9-10 streptavidin 2D crystal surface 201-203 stress fibers (SFs) 347 - intracellular mechanical manipulation – AFM used as lateral force microscope 338 - 340under lateral force application 340 - 343subharmonics 145 substrate surfaces 200 streptavidin 2D crystal surface 201–203 - supported planar lipid bilayers 200-201 surface chemistry 234-235 surface force apparatus 70 suspension of small unilamellar vesicles (SUVs) 260

t

181 t" events 318-319 tapping mode 22 thermal drift 315 thermal excitation 128, 130 thermally driven vibration 132-133 thermal methods 101 thermal noise method 311 tip dilation 28 tip-sample interaction 121-122, 128, 131, 135, 137, 140, 143, 147, 148, 150 titin 177-180 total internal reflection fluorescence microscopy 211, 218, 219, 220-221 - optical setup 218-220 Triton-treated cells 334 Trx enzymes 181 tube scanners 6-7 tuning fork method 16-17

ν

van der Waals forces 66, 72 vascular smooth muscle cells (VSMCs) 213, 216, 217, 221, 223 voltage-controlled oscillator (VCO) 90

w

water distribution 114-116 Wormlike chain 170-171 Wsc-domain 288

Y

yeast

- cell wall integrity sensors 286–288
- probe of single sensors in live cells
- – imaging sensor clustering 295–298
- sensor spring properties measurement 292–295
- use of sensors as molecular rulers 298–302
- sensor to surface 291–292

z

zymolyase 302