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Force measurements with the atomic force microscope: Technique, interpretation and applications

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Abbreviations: AFM, atomic force microscope; AOT, bis(2-ethylhexyl)sulfosuccinate; BSA, bovine serum albumin; CMC, critical micellar concentration (mol/L); CSH, calcium silicate hydrate; CTAB, cetyltrimethylammonium bromide (=hexadecyltrimethylammonium bromide); DDAB, didodecyl dimethylammonium bromide; DDAPS, *N*-dodecyl-*N*,*N*-dimethyl-3-ammonio-1-propanesulfonate; DGDG, digalactosyldiglyceride; DLVO, Derjaguin–Landau–Verwey–Overbeek theory; DMA, dynamical mechanical analysis; DMT, Derjaguin–Müller–Toporov theory of mechanical contact; DNA, desoxyribonucleic acid; DODAB, dimethyl-dioctadecylammonium bromide; DOPC, 1,2-dioleoyl-*sn*-glycero-3-phosphocholine; DOPE, 1,2-dioleoyl-*sn*-glycero-3-phosphodylethanolamine; DOPS, 1,2-dioleoyl-*sn*-glycero-3-phospho-l-serine; DOTAP, 1,2-dioleoyl-3-trimethylammonium-propane chloride; DTAB, dodecyltrimethylammonium bromide; DSCG, disodium cromoglycate; DSPE, 1,2-distearoyl-*sn*-glycero-3-phosphoethanolamine; EDTA, ethylenediaminetetraacetic acid; FJC, freely jointed chain; HOPG, highly oriented pyrolytic graphite; HSA, human serum albumin; JKR, Johnson–Kendall–Roberts theory of mechanical contact; LPS, lipopolysaccharides; MD, molecular dynamics; MEMS, micro-electromechanical systems; MF, melamine formaldehyde; MGDG, monogalactosyldiacylglycerol; OMCTS, octamethylcyclotetrasiloxane, $((CH_2)_2SiO)_4$; OTS, octadecyltrichlorosilane; PAA, poly(acrylic acid); PAH, poly(allyl amine hydrochloride); PBA, parallel beam approximation; PBMA, poly(*n*-butyl methacrylate), $–(CH_2CC_4H_9COOCH_3)_n–$; PDADMAC, poly(diallyl-dimethyl-ammonium chloride); PDMS, poly(dimethylsiloxane); PEG, polyethylene glycol; PEI, polyethyleneimine; PEO, polyethyleneoxide, $–(OCH_2CH_2)_n–$; PFM, pulsed force mode; PLA, polylactic acid; PMAA, poly(methacrylic acid), $–(CH_2CHCOOH)_n–$; PMC, polyelectrolyte microcapsules; PMMA, poly(methyl methacrylate), $–(CH_2CCH_3COOCH_3)_n–$; PP, poly(propylene), $–(CH_2CHCH_3)_n–$; PS, polystyrene, $–(CH_2–CH(C_6H_5))_n–$; PSD, position sensitive detector; PSS, poly(sodium styrenesulfonate); PSU, polysulfonate; PTFE, poly(tetrafluoroethylene); PVD, physical vapor deposition; PVP, poly(vinylpyridine), $–(CH_2CHC_5NH_4)_n–$; SAM, self-assembled monolayer; SDS, sodium dodecylsulfate; SEDS, solution-enhanced dispersion by supercritical fluids; SEM, scanning electron microscope; SFA, surface forces apparatus; SNOM, scanning near-field optical microscope; STM, scanning tunneling microscope; TEM, transmission electron microscope; TIRM, total internal reflection microscopy; TTAB, tetradecyl trimethylammonium bromide; UHV, ultra-high vacuum; WLC, wormlike chain; XPS, X-ray photoelectron spectroscopy

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Nomenclature

a	contact radius (m)
a_{Hertz}	contact radius in the Hertz theory
A	area (m^2)
A_H	Hamaker constant (J)
A_1	area between the two contact lines above the axis $F = 0$
A_2	area between the retraction contact lines and the axis $F = 0$
b	slip length (m)
c	speed of light in vacuum (2.998×10^8 m/s), concentration (mol/L)
C	capacitance of tip and sample (F); constant of the atom–atom pair potential (J m^6)
C_K, C_D, C_L	Keesom, Debye, and London coefficients (J m^6)
d	distance between end of cantilever and PSD
D	tip–sample distance (m)
D_{jtc}	tip–sample distance at which the jump-to-contact occurs (m)
D_0	typical interatomic spacing (m)
e	unit charge (1.602×10^{-19} C)
E	Young's modulus (Pa)
E_F, E_S	Young' modulus of film and substrate (Pa)
E_t, E_s	Young's modulus of tip and sample material (Pa)
E_{tot}	reduced Young's modulus Eq. (4.4) (Pa)
f	force per unit area (Pa)
f^*	dimensionless correction factor
F	force (N)
F_{ad}	adhesion force (N)
F_{av}	average force (N)
F_{cap}	capillary force (N)
F_{el}	double-layer force (N)
F_H	hydrodynamic force (N)
F_{surf}	distance-dependent surface force (N)
F_0	mean rupture force (N)
h	Planck's constant (6.626×10^{-34} J s); thickness of a film on a substrate (m)
H	height of tip (m); hardness (Pa)
H_d	height of a deformed polyelectrolyte microcapsule (m)
I	$wt_c^3/12$, moment of inertia of a cantilever (m^4)
I_{PSD}	photosensor current (A)
J	relative Young' modulus, Eq. (4.12)
k_B	Boltzmann constant (1.381×10^{-23} J/K)
k_c	spring constant of cantilever (N/m)
k_{eff}	$=k_c k_s/(k_c + k_s)$ effective spring constant (N/m)
k_s	sample stiffness (N/m)
k_0	frequency of spontaneous hole formation (Hz)
l	length of one segment in a linear polymer (m)