

# Contents

Acknowledgements.....	xi
List of Figures.....	xiii
List of Tables.....	xxi

<b>CHAPTER 1 Introduction to Metrology for Advanced Manufacturing and Micro- and Nanotechnology .....</b>	<b>1</b>
1.1 What is engineering nanometrology?.....	4
1.2 The contents of this book and differences to edition 1 .....	4
References .....	5

<b>CHAPTER 2 Some Basics of Measurement .....</b>	<b>7</b>
2.1 Introduction to measurement.....	7
2.2 Units of measurement and the SI.....	9
2.3 Length .....	10
2.4 Mass .....	14
2.5 Force .....	15
2.6 Angle.....	16
2.7 Traceability .....	18
2.8 Accuracy, precision, resolution, error and uncertainty.....	19
2.8.1 Accuracy and precision .....	20
2.8.2 Resolution and error .....	21
2.8.3 Uncertainty in measurement.....	22
2.9 The laser.....	28
2.9.1 Theory of the helium–neon laser .....	28
2.9.2 Single-mode laser wavelength stabilisation schemes .....	30
2.9.3 Laser frequency stabilisation using saturated absorption.....	30
2.9.4 Zeeman-stabilised 633 nm lasers.....	33
2.9.5 Frequency calibration of a (stabilised) 633 nm laser.....	34
2.9.6 Modern and future laser frequency standards.....	35
References .....	36

<b>CHAPTER 3 Precision Measurement Instrumentation – Some Design Principles .....</b>	<b>41</b>
3.1 Geometrical considerations .....	42
3.2 Kinematic design .....	43
3.2.1 The Kelvin clamps.....	44
3.2.2 A single degree of freedom motion device.....	46

## Contents

<b>3.3</b>	Dynamics .....	47
<b>3.4</b>	The Abbe principle .....	48
<b>3.5</b>	Elastic compression .....	49
<b>3.6</b>	Force loops.....	51
3.6.1	The structural loop.....	51
3.6.2	The thermal loop.....	51
3.6.3	The metrology loop.....	51
<b>3.7</b>	Materials.....	52
3.7.1	Minimising thermal inputs.....	52
3.7.2	Minimising mechanical inputs.....	53
<b>3.8</b>	Symmetry .....	54
<b>3.9</b>	Vibration isolation .....	54
3.9.1	Sources of vibration.....	55
3.9.2	Passive vibration isolation.....	56
3.9.3	Damping.....	58
3.9.4	Internal resonances .....	58
3.9.5	Active vibration isolation .....	58
3.9.6	Acoustic noise.....	59
	References .....	59

<b>CHAPTER 4</b>	<b>Length Traceability Using Interferometry .....</b>	<b>63</b>
<b>4.1</b>	Traceability in length.....	64
<b>4.2</b>	Gauge blocks – both a practical and traceable artefact .....	65
<b>4.3</b>	Introduction to interferometry .....	67
4.3.1	Light as a wave.....	67
4.3.2	Beat measurement when $\omega_1 \neq \omega_2$ .....	69
4.3.3	Visibility and contrast .....	69
4.3.4	White light interference and coherence length .....	70
<b>4.4</b>	Interferometer designs .....	72
4.4.1	The Michelson and Twyman–Green interferometer.....	72
4.4.2	The Fizeau interferometer .....	74
4.4.3	The Jamin and Mach–Zehnder interferometers .....	77
4.4.4	The Fabry–Pérot interferometer .....	78
<b>4.5</b>	Measurement of gauge blocks by interferometry .....	80
4.5.1	Gauge blocks and interferometry .....	80
4.5.2	Gauge block interferometry.....	81
4.5.3	Operation of a gauge block interferometer.....	83
4.5.4	Sources of error in gauge block interferometry.....	88
4.5.5	Alternative approaches .....	90
	References .....	92

<b>CHAPTER 5 Displacement Measurement</b> .....	95
<b>5.1</b> Introduction to displacement measurement .....	96
<b>5.2</b> Basic terms.....	96
<b>5.3</b> Displacement interferometry .....	97
5.3.1 Basics of displacement interferometry.....	97
5.3.2 Homodyne interferometry.....	98
5.3.3 Heterodyne interferometry.....	99
5.3.4 Fringe counting and subdivision .....	100
5.3.5 Double-pass interferometry.....	101
5.3.6 Differential interferometry.....	102
5.3.7 Swept-frequency absolute distance interferometry.....	103
5.3.8 Sources of error in displacement interferometry.....	104
5.3.9 Latest advances in displacement interferometry.....	110
5.3.10 Angular interferometers.....	112
<b>5.4</b> Strain sensors .....	113
<b>5.5</b> Capacitive displacement sensors .....	115
<b>5.6</b> Eddy current and inductive displacement sensors .....	116
<b>5.7</b> Optical encoders.....	118
<b>5.8</b> Optical fibre sensors .....	120
<b>5.9</b> Other optical displacement sensors .....	123
<b>5.10</b> Calibration of displacement sensors .....	123
5.10.1 Calibration using optical interferometry .....	123
5.10.2 Calibration using X-ray interferometry.....	125
References .....	127
<b>CHAPTER 6 Surface Topography Measurement</b>	
<b>Instrumentation</b> .....	133
<b>6.1</b> Introduction to surface topography measurement.....	134
<b>6.2</b> Spatial wavelength ranges .....	135
<b>6.3</b> Historical background of classical surface texture measuring instrumentation .....	137
<b>6.4</b> Surface profile measurement.....	139
<b>6.5</b> Areal surface texture measurement.....	140
<b>6.6</b> Surface topography measuring instrumentation.....	142
6.6.1 Stylus instruments.....	143
<b>6.7</b> Optical instruments.....	146
6.7.1 Limitations of optical instruments .....	146
6.7.2 Scanning optical techniques .....	152
6.7.3 Areal optical techniques .....	162
6.7.4 Scattering instruments .....	172
<b>6.8</b> Capacitive instruments .....	175

## Contents

<b>6.9</b>	Pneumatic instruments.....	175
<b>6.10</b>	Calibration of surface topography measuring instruments .....	176
6.10.1	Traceability of surface topography measurements.....	176
6.10.2	Material measures for profile measuring instruments.....	178
6.10.3	Material measures for areal surface texture measuring instruments.....	180
<b>6.11</b>	Uncertainties in surface topography measurement.....	186
<b>6.12</b>	Metrological characteristics .....	187
<b>6.13</b>	Comparisons of surface topography measuring instruments .....	189
<b>6.14</b>	Determination of the spatial frequency response .....	191
<b>6.15</b>	Software measurement standards.....	192
	References .....	193

<b>CHAPTER 7</b>	<b>Scanning Probe and Particle Beam Microscopy .....</b>	<b>205</b>
<b>7.1</b>	Scanning probe microscopy .....	207
<b>7.2</b>	Scanning tunnelling microscopy .....	208
<b>7.3</b>	Atomic force microscopy .....	209
7.3.1	Noise sources in atomic force microscopy .....	211
7.3.2	Some common artefacts in AFM imaging.....	213
7.3.3	Determining the coordinate system of an AFM .....	215
7.3.4	Traceability of atomic force microscopy .....	216
7.3.5	Force measurement with AFMs .....	217
7.3.6	AFM cantilever calibration .....	220
7.3.7	Inter- and intra-molecular force measurement using AFM.....	220
7.3.8	Tip–sample distance measurement .....	224
7.3.9	Challenges and artefacts in AFM force measurements.....	225
<b>7.4</b>	Examples of physical properties measurement using AFM .....	226
7.4.1	Thermal measurement .....	226
7.4.2	Electrical resistivity measurement .....	226
<b>7.5</b>	Scanning probe microscopy of nanoparticles .....	227
<b>7.6</b>	Electron microscopy .....	228
7.6.1	Scanning electron microscopy.....	228
7.6.2	Transmission electron microscopy.....	230
7.6.3	Traceability and calibration of TEMs.....	230
7.6.4	Electron microscopy of nanoparticles.....	232
<b>7.7</b>	Other particle beam microscopy techniques .....	235
	References .....	236

<b>CHAPTER 8</b>	<b>Surface Topography Characterisation</b> .....	241
8.1	Introduction to surface topography characterisation.....	242
8.2	Surface profile characterisation.....	243
8.2.1	Evaluation length.....	244
8.2.2	Total traverse length.....	244
8.2.3	Profile filtering .....	245
8.2.4	Default values for profile characterisation.....	247
8.2.5	Profile characterisation and parameters .....	248
8.2.6	Amplitude profile parameters (peak to valley).....	249
8.2.7	Amplitude parameters (average of ordinates).....	252
8.2.8	Spacing parameters.....	255
8.2.9	Curves and related parameters .....	256
8.2.10	Profile specification standards.....	259
8.3	Areal surface texture characterisation .....	261
8.3.1	Scale-limited surface .....	261
8.3.2	Areal filtering .....	262
8.3.3	Areal specification standards.....	264
8.3.4	Unified coordinate system for surface texture and form.....	267
8.3.5	Areal parameters.....	267
8.3.6	Field parameters .....	268
8.3.7	Feature characterisation.....	275
8.4	Fractal methods.....	283
8.4.1	Linear fractal methods.....	284
8.4.2	Areal fractal analysis .....	286
8.5	Comparison of profile and areal characterisation.....	289
	References .....	290
<b>CHAPTER 9</b>	<b>Coordinate Metrology</b> .....	295
9.1	Introduction to CMMs.....	295
9.1.1	CMM probing systems .....	298
9.1.2	CMM software.....	298
9.1.3	CMM alignment .....	299
9.1.4	CMMs and CAD.....	299
9.1.5	Prismatic against free form .....	299
9.1.6	Other types of CMM .....	300
9.2	Sources of error on CMMs.....	300
9.3	Traceability, calibration and performance verification of CMMs.....	301
9.3.1	Traceability of CMMs .....	302
9.4	Micro-CMMs .....	303
9.4.1	Stand-alone micro-CMMs .....	304

## Contents

<b>9.5</b>	Micro-CMM probes .....	307
9.5.1	Mechanical micro-CMM probes .....	308
9.5.2	Silicon-based probes .....	310
9.5.3	Optomechanical probes .....	312
9.5.4	Vibrating probes .....	314
<b>9.6</b>	Verification and calibration of micro-CMMs .....	316
9.6.1	Calibration of laser interferometer-based micro-CMMs .....	319
9.6.2	Calibration of linescale-based micro-CMMs .....	319
	References .....	321
<b>CHAPTER 10</b>	<b>Mass and Force Measurement .....</b>	<b>327</b>
<b>10.1</b>	Traceability of traditional mass measurement .....	328
10.1.1	Manufacture of the kilogram weight and the original copies .....	328
10.1.2	Surface texture of mass standards .....	330
10.1.3	Dissemination of the kilogram .....	330
10.1.4	Post nettoyage—lavage stability .....	330
10.1.5	Limitations of the current definition of the kilogram .....	331
10.1.6	Investigations into an alternative definition of the kilogram .....	332
10.1.7	Mass comparator technology .....	334
<b>10.2</b>	Low-mass measurement .....	335
10.2.1	Weighing by subdivision .....	336
<b>10.3</b>	Low-force measurement .....	336
10.3.1	Relative magnitude of low forces .....	336
10.3.2	Traceability of low-force measurements .....	337
10.3.3	Primary low-force balances .....	339
10.3.4	Low-force transfer artefacts .....	340
	References .....	347
	Appendix A: SI Units of Measurement and Their Realisation at NPL .....	351
	Appendix B: SI Derived Units .....	353
	Index .....	355