

Contents

Foreword	xiii
Preface	xv
Acknowledgments	xvii
1 Introduction to Spectroscopic Ellipsometry	1
1.1 Features of Spectroscopic Ellipsometry	1
1.2 Applications of Spectroscopic Ellipsometry	3
1.3 Data Analysis	5
1.4 History of Development	7
1.5 Future Prospects	9
References	10
2 Principles of Optics	13
2.1 Propagation of Light	13
2.1.1 Propagation of One-Dimensional Waves	13
2.1.2 Electromagnetic Waves	18
2.1.3 Refractive Index	19
2.2 Dielectrics	24
2.2.1 Dielectric Polarization	24
2.2.2 Dielectric Constant	25
2.2.3 Dielectric Function	29
2.3 Reflection and Transmission of Light	32
2.3.1 Refraction of Light	32
2.3.2 p- and s-Polarized Light Waves	33
2.3.3 Reflectance and Transmittance	39
2.3.4 Brewster Angle	40
2.3.5 Total Reflection	42
2.4 Optical Interference	43
2.4.1 Optical Interference in Thin Films	43
2.4.2 Multilayers	46
References	48
3 Polarization of Light	49
3.1 Representation of Polarized Light	49
3.1.1 Phase of Light	49
3.1.2 Polarization States of Light Waves	50

3.2 Optical Elements	52
3.2.1 Polarizer (Analyzer)	53
3.2.2 Compensator (Retarder)	57
3.2.3 Photoelastic Modulator	58
3.2.4 Depolarizer	59
3.3 Jones Matrix	60
3.3.1 Jones Vector	60
3.3.2 Transformation of Coordinate Systems	62
3.3.3 Jones Matrices of Optical Elements	66
3.3.4 Representation of Optical Measurement by Jones Matrices	68
3.4 Stokes Parameters	70
3.4.1 Definition of Stokes Parameters	70
3.4.2 Poincaré Sphere	72
3.4.3 Partially Polarized Light	75
3.4.4 Mueller Matrix	77
References	78
4 Principles of Spectroscopic Ellipsometry	81
4.1 Principles of Ellipsometry Measurement	81
4.1.1 Measured Values in Ellipsometry	81
4.1.2 Coordinate System in Ellipsometry	84
4.1.3 Jones and Mueller Matrices of Samples	86
4.2 Ellipsometry Measurement	87
4.2.1 Measurement Methods of Ellipsometry	87
4.2.2 Rotating-Analyzer Ellipsometry (RAE)	93
4.2.3 Rotating-Analyzer Ellipsometry with Compensator	97
4.2.4 Rotating-Compensator Ellipsometry (RCE)	99
4.2.5 Phase-Modulation Ellipsometry (PME)	104
4.2.6 Infrared Spectroscopic Ellipsometry	106
4.2.7 Mueller Matrix Ellipsometry	111
4.2.8 Null Ellipsometry and Imaging Ellipsometry	113
4.3 Instrumentation for Ellipsometry	117
4.3.1 Installation of Ellipsometry System	117
4.3.2 Fourier Analysis	120
4.3.3 Calibration of Optical Elements	122
4.3.4 Correction of Measurement Errors	127
4.4 Precision and Error of Measurement	130
4.4.1 Variation of Precision and Error with Measurement Method	131
4.4.2 Precision of (ψ, Δ)	135
4.4.3 Precision of Film Thickness and Absorption Coefficient	137
4.4.4 Depolarization Effect of Samples	139
References	141

5 Data Analysis	147
5.1 Interpretation of (ψ, Δ)	147
5.1.1 Variations of (ψ, Δ) with Optical Constants	147
5.1.2 Variations of (ψ, Δ) in Transparent Films	150
5.1.3 Variations of (ψ, Δ) in Absorbing Films	155
5.2 Dielectric Function Models	158
5.2.1 Lorentz Model	160
5.2.2 Interpretation of the Lorentz Model	162
5.2.3 Sellmeier and Cauchy Models	170
5.2.4 Tauc–Lorentz Model	170
5.2.5 Drude Model	173
5.2.6 Kramers–Kronig Relations	176
5.3 Effective Medium Approximation	177
5.3.1 Effective Medium Theories	177
5.3.2 Modeling of Surface Roughness	181
5.3.3 Limitations of Effective Medium Theories	184
5.4 Optical Models	187
5.4.1 Construction of Optical Models	187
5.4.2 Pseudo-Dielectric Function	189
5.4.3 Optimization of Sample Structures	191
5.4.4 Optical Models for Depolarizing Samples	191
5.5 Data Analysis Procedure	196
5.5.1 Linear Regression Analysis	196
5.5.2 Fitting Error Function	199
5.5.3 Mathematical Inversion	200
References	204
6 Ellipsometry of Anisotropic Materials	209
6.1 Reflection and Transmission of Light by Anisotropic Materials	209
6.1.1 Light Propagation in Anisotropic Media	209
6.1.2 Index Ellipsoid	213
6.1.3 Dielectric Tensor	215
6.1.4 Jones Matrix of Anisotropic Samples	217
6.2 Fresnel Equations for Anisotropic Materials	222
6.2.1 Anisotropic Substrate	222
6.2.2 Anisotropic Thin Film on Isotropic Substrate	224
6.3 4×4 Matrix Method	226
6.3.1 Principles of the 4×4 Matrix Method	226
6.3.2 Calculation Method of Partial Transfer Matrix	232
6.3.3 Calculation Methods of Incident and Exit Matrices	233
6.3.4 Calculation Procedure of the 4×4 Matrix Method	236
6.4 Interpretation of (ψ, Δ) for Anisotropic Materials	237
6.4.1 Variations of (ψ, Δ) in Anisotropic Substrates	237
6.4.2 Variations of (ψ, Δ) in Anisotropic Thin Films	241

6.5	Measurement and Data Analysis of Anisotropic Materials	243
6.5.1	Measurement Methods	243
6.5.2	Data Analysis Methods	245
	References	246
7	Data Analysis Examples	249
7.1	Insulators	249
7.1.1	Analysis Examples	249
7.1.2	Advanced Analysis	252
7.2	Semiconductors	256
7.2.1	Optical Transitions in Semiconductors	256
7.2.2	Modeling of Dielectric Functions	258
7.2.3	Analysis Examples	262
7.2.4	Analysis of Dielectric Functions	268
7.3	Metals/Semiconductors	276
7.3.1	Dielectric Function of Metals	276
7.3.2	Analysis of Free-Carrier Absorption	281
7.3.3	Advanced Analysis	286
7.4	Organic Materials/Biomaterials	287
7.4.1	Analysis of Organic Materials	287
7.4.2	Analysis of Biomaterials	292
7.5	Anisotropic Materials	294
7.5.1	Analysis of Anisotropic Insulators	295
7.5.2	Analysis of Anisotropic Semiconductors	296
7.5.3	Analysis of Anisotropic Organic Materials	299
	References	303
8	Real-Time Monitoring by Spectroscopic Ellipsometry	311
8.1	Data Analysis in Real-Time Monitoring	311
8.1.1	Procedures for Real-Time Data Analysis	312
8.1.2	Linear Regression Analysis (LRA)	313
8.1.3	Global Error Minimization (GEM)	317
8.1.4	Virtual Substrate Approximation (VSA)	323
8.2	Observation of Thin-Film Growth by Real-Time Monitoring	328
8.2.1	Analysis Examples	328
8.2.2	Advanced Analysis	331
8.3	Process Control by Real-Time Monitoring	333
8.3.1	Data Analysis in Process Control	334
8.3.2	Process Control by Linear Regression Analysis (LRA)	334
8.3.3	Process Control by Virtual Substrate Approximation (VSA)	340
	References	342

Appendices

1 Trigonometric Functions	345
2 Definitions of Optical Constants	347
3 Maxwell's Equations for Conductors	349
4 Jones–Mueller Matrix Conversion	353
5 Kramers–Kronig Relations	357
Index	361

The book chapters on polarization, the Jones–Mueller matrix conversion, and Kramers–Kronig relations are intended to be introductory, but also well informed, with over 200 figures, making this an excellent practical textbook for learning ellipsometry at both the undergraduate and intermediate to advanced levels. The book will be appropriate as a text in an educational institution, but it will be valuable to help educate and train scientists in optics and industrial applications to learn practical applications of the techniques.

For decades the book, *Polarimetry and Ellipticity Light*, by R. A. Fournier and R. M. Fournier (John Wiley, New York, 1977), has probably been the most widely cited general reference on ellipsometry. However, this book is now 30 years old and out of print. Furthermore, a book offers the reader a modern up-to-date summary discussion of many of the same topics: fundamentals of optical polarimetry and ellipsometry, as well as new chapters. This volume naturally into more advanced and well-referenced chapters on data analysis, anisotropy, experimental examples, and infrared ellipsometry.

A perspective of the role of Fournier's book in the context of existing literature on ellipsometry might be helpful. Often cited references on ellipsometry are:

- * *Infrared Spectroscopic Ellipsometry* by J. Poppoer, (Akademie-Verlag, Berlin, 1991).
- * *Selected Papers on Ellipsometry*, R. M. A. Azam, Ed., SPIE Milestone Series, Vol. 21, (SPIE, Bellingham, 1990).
- * *Modern Ellipsometry: An Aid to the Study of Electronic Processes and Components of Characterization of Electronic and Electrochemical Processes*, J. A. van der Steene, Ed., Academic Press, Inc., New York, 1971.
- * *Handbook Technical Data on Infrared Spectroscopic Ellipsometry and Polarimetry*, Arthur Ganz, Chem. Verlag, Berlin, Germany, 1979.

These are just recent books for spectroscopic ellipsometry. These include: N. G. McCollum, *Ellipsometry and Polarimetry: Basic Principles, Phenomena, and Applications*, Springer, Berlin, Heidelberg, and London, 2009.