

Contents

Preface *XI*

1	Introduction	1
2	Propagation of Light and Other Electromagnetic Waves	7
2.1	Properties of Electromagnetic Waves	7
2.2	Huygens–Fresnel Principle	14
2.3	Interference of Electromagnetic Waves	15
2.4	Reflection and Refraction	16
2.5	Diffraction	21
2.5.1	Transmission Gratings	27
2.5.1.1	Lamellar Transmission Gratings	27
2.5.1.2	Holographic Transmission Gratings	29
2.5.2	Reflection Gratings	31
2.5.2.1	Lamellar Reflection Gratings	31
2.5.2.2	Blazed Gratings	33
2.5.2.3	Holographic Gratings	34
2.6	Scattering	34
2.7	Dielectric Function and Refractive Index	35
2.7.1	Models for the Dielectric Function	35
2.7.2	Kramers–Kronig Analysis of Dielectric Functions	49
2.7.3	Empiric Formulas for the Refractive Index	50
2.7.4	EMA Models	53
3	Spectral Reflectance and Transmittance of a Layer Stack	59
3.1	Reflectance and Transmittance of a Single Layer	59
3.1.1	Coherent Superposition of Reflected Light	59
3.1.2	Influence of Absorption on the Layer	65
3.1.3	Partial Incoherence due to Thick Substrates	69
3.1.4	Partial Incoherence due to Roughness	72
3.1.5	Coherent Superposition of Transmitted Light	74
3.2	Propagating Wave Model for a Layer Stack	75
3.2.1	Coherent Reflectance and Transmittance of a Layer Stack	76

3.2.2	Consideration of Incoherent Substrates	78
3.2.3	Consideration of Surface Roughness	78
3.2.4	r - t - ϕ Model for a Layer Stack	79
4	The Optical Measurement	81
4.1	Spectral Reflectance and Transmittance Measurement	81
4.2	Ellipsometric Measurement	85
4.3	Other Optical Methods	88
4.3.1	Prism Coupling	88
4.3.2	Chromatic Thickness Determination	92
4.4	Components for the Optical Measurement	94
4.4.1	Light Sources	94
4.4.1.1	Halogen Lamps	94
4.4.1.2	White Light LED	95
4.4.1.3	Superluminescence Diodes	96
4.4.1.4	Xenon High-Pressure Arc Lamps	97
4.4.1.5	Deuterium Lamps	97
4.4.2	Optical Components	99
4.4.2.1	Lenses and Mirrors	99
4.4.2.2	Polarizers and Analyzers	101
4.4.2.3	Optical Retarders	102
4.4.3	Optical Fibers	103
4.4.4	Miniaturized Spectrometers	107
4.4.4.1	Gratings	107
4.4.4.2	Detectors	110
4.4.4.3	System Properties	115
5	Thin-Film Thickness Determination	121
5.1	Fast Fourier Transform	122
5.1.1	Single Layer	122
5.1.2	Layer Stack	129
5.1.3	Accuracy, Resolution, Repeatability, and Reproducibility	130
5.2	Regression Analysis with χ^2 -Test	131
5.2.1	Method of Thickness Determination	131
5.2.2	Accuracy, Resolution, Repeatability, and Reproducibility	137
6	The Color of Thin Films	141
7	Applications	149
7.1	High-Reflection and Antireflection Coatings	150
7.1.1	HR Coatings on Metallic Mirrors	151
7.1.2	AR Coatings on Glass	152
7.1.3	AR Coatings on Solar Wafers	153
7.2	Thin Single- and Double-Layer Coatings	156
7.2.1	SiO ₂ on Silicon Wafers	157

7.2.2	Si_3N_4 Hardcoat	157
7.2.3	Double-Layer System	158
7.2.4	Porous Silicon on Silicon	158
7.3	Photoresists and Photolithographic Structuring	160
7.4	Thickness of Wafers and Transparent Plastic Films	163
7.4.1	Thickness of Semiconductor, Glass, and Sapphire Wafers	163
7.4.2	Thickness of Transparent Plastic Films	167
7.4.3	Thickness of Doped Silicon	169
7.5	Silicon on Insulator	174
7.6	Thin-Film Photovoltaics	177
7.6.1	Inorganic Thin-Film Solar Cells	177
7.6.2	Organic Thin-Film Solar Cells	180
7.7	Measurement of Critical Dimensions	182

Numerics with Complex Numbers 187

Fourier Transform 191

Levenberg–Marquardt Algorithm 197

Downhill Simplex Algorithm 199

References 201

Index 209