

Contents

1 Introduction	1
References	3
2 Global Energy Situation	5
2.1 Primary Energy Resources	5
2.2 Primary Energy Demand	6
2.3 Production of Solar Cells and Modules	7
References	8
3 Sun as Energy Source	9
3.1 Geometrical Configuration	9
3.2 Spectral Distribution of Solar Photons	10
3.2.1 Thermal Equilibrium Radiation/Planck's Law	10
3.2.2 Emission from a Black Body	15
3.3 Radiative Balance Between Sun and Earth	17
3.4 Particular Aspects of Solar Radiation Arriving at the Earth	20
3.4.1 Solar Energy Flux	20
3.4.2 Photon Flux at the Position of the Earth	21
3.4.3 Optical Concentration of Solar Light	21
3.4.4 Average Energy of Solar Photons	24
3.4.5 Fraction of Solar Photons Above a Specific Optical Threshold Energy	25
3.4.6 Momentum Transfer of Solar Photons to Absorbers	25
3.4.7 How an Earth-Based Observer Sees the Sun	27
3.4.8 Entropy Flux of Solar Radiation	28
3.4.9 Chemical Potential of Light	30
3.4.10 Kirchhoff's Law for Non-ideal Black Bodies	35
3.4.11 Spectrally Selective Radiators and Absorbers	36
References	37

4	Theoretical Limits for Solar Light Conversion	39
4.1	Endoreversible Thermodynamics	40
4.1.1	Curzon–Ahlborn Approach	41
4.1.2	Stefan–Boltzmann Approach	44
4.1.3	Maximum Conversion Efficiency of Black Body Radiation with a Thermal Receiver in the Limit of Vanishing Output Power	46
4.1.4	Mueser Approach	49
4.1.5	Temperatures and Limits of Efficiency for Planets of the Solar System	52
4.1.6	Spectrally Selective Absorbers/Emitters	54
4.1.7	Multispectral Solar Light Conversion	56
4.2	Electronic Band Systems for Solar Light Conversion	58
4.2.1	Electronic Band System in Thermal Equilibrium	60
4.2.2	Quasi-Fermi Levels in Electronic Band Systems	63
4.2.3	Electronic Band System Exposed to Solar Radiation	66
4.2.4	Carrier Extraction From an Illuminated Electronic Band System	69
4.2.5	Ideal Photovoltaic Converter	73
4.2.6	Optical Absorption in Band Systems	83
4.2.7	Reversal of Photon and Carrier Fluxes	92
4.2.8	Irreversibilities in Solar Light Conversion	95
4.2.9	Gradients in Quasi-Fermi Levels for Charge Transport	103
	References	106
5	Real Photovoltaic Converters	109
5.1	Homogeneous <i>pn</i> -Junctions	110
5.1.1	Space-Charge Region	110
5.1.2	Current Density–Voltage Relation of a Homogeneous <i>pn</i> -Diode	115
5.1.3	Illuminated Homogeneous <i>pn</i> -Diode	120
5.1.4	Comparison of Homogeneous <i>pn</i> -Junctions with the Ideal Converter	121
5.1.5	Upper Limits of the Open-Circuit Voltage Achievable in <i>pn</i> -Junctions	123
5.1.6	Ideality Factor of Diodes	125
5.1.7	Relevance of Space Charge Region for Charge Separation	128
5.1.8	So-Called Back Surface Field	131
5.2	Heterojunctions	134
5.2.1	Concept of Heterojunctions	134
5.2.2	Electronic Properties of Heterojunctions	136
5.3	pin Diodes	137
5.3.1	Concept of pin Diodes	137
5.3.2	Space-Charge Region in Real pin Diodes	138
5.3.3	Charge Separation by Gradients of Quasi-Fermi Levels	139

5.4	Schottky Diodes	140
5.4.1	Space-Charge Region and Band Diagram	140
5.4.2	Illuminated Schottky Diode	145
5.5	Excitons and Subsequent Charge Transfer in Organic Absorbers	148
5.5.1	General Aspects of Light Absorption and Generation of Excited States	149
5.5.2	Barriers with Organic Absorbers	151
5.6	Photo-Electrochemical and Photochemical Cells	155
5.6.1	Photo-Electrochemical Cells	155
5.6.2	Photochemical Cells	156
5.7	Optical Absorption in Real Systems	157
5.7.1	Absorption Coefficient and Lambert–Beer Law	157
5.7.2	Optimum Thickness of Absorber Layers	158
5.7.3	Absorption of Semiconductors Versus Molecules or Atoms	160
5.8	Equivalent Circuit of Illuminated Diodes	162
5.9	Status of Cell and Module Efficiencies	165
	References	166
6	Advanced Concepts: Beyond the Shockley–Queisser Limit	167
6.1	Concentration of Sunlight	167
6.1.1	Imaging Concentration of Sunlight	168
6.1.2	Non-imaging Concentration of Sunlight	168
6.1.3	Non-imaging Concentration with Stokes Shift/Fluorescence Collectors	170
6.1.4	Optical Design for Increase of the Photon Density in Matter	175
6.1.5	Photonic Crystal Stop Gaps to Reduce Luminescence Emission	177
6.2	Multispectral Conversion	179
6.2.1	Traditional Spectrum Splitting	179
6.2.2	Spectrum Splitting by Optical Components	184
6.2.3	Subdivision of a Homogeneous Single Gap Absorber	185
6.3	Photon Conversion	187
6.3.1	Photon Up-Conversion	187
6.3.2	Photon Down-Conversion	188
6.4	Intermediate-Band-Gap Cells	189
6.5	Use of Photon Excess Energy	191
6.5.1	Hot Carriers	191
6.6	Plasmonic Effects for Increase in Local Photon Density	196
6.6.1	Plasmons in Small Metal Clusters	196
6.6.2	Local Increase in Photon Density	197
6.7	Thermophotovoltaic Energy Conversion	198
	References	199

A	Radiation in Condensed Matter	201
A.1	Propagation and Attenuation	201
A.2	Propagation Across Interfaces	203
A.3	Matrix Transfer Formalism	205
B	Absorption of Photons in Condensed Matter	207
	Reference	209
C	Photon Density in Matter	211
	Reference	212
D	Surface Recombination and Carrier Depth Profiles	213
D.1	Carrier Flux at the Surface	213
D.2	Surface Recombination and Carrier Diffusion	215
E	Finite Length of a Homogeneous Diode	219
	References	220
F	Boltzmann Transport Equation	221
	References	223
	Index	225

<http://www.springer.com/978-3-662-46683-4>

Photovoltaic Solar Energy Conversion

Bauer, G.H.

2015, XIII, 227 p. 144 illus., 124 illus. in color., Softcover

ISBN: 978-3-662-46683-4