

Contents

List of Symbols *IX*

Preface *XI*

1	Problems of the Energy Economy	<i>1</i>
1.1	Energy Economy	<i>1</i>
1.2	Estimate of the Maximum Reserves of Fossil Energy	<i>4</i>
1.3	The Greenhouse Effect	<i>6</i>
1.3.1	Combustion	<i>6</i>
1.3.2	The Temperature of the Earth	<i>7</i>
1.4	Problems	<i>9</i>
2	Photons	<i>11</i>
2.1	Black-body Radiation	<i>11</i>
2.1.1	Photon Density n_γ in a Cavity (Planck's Law of Radiation)	<i>12</i>
2.1.2	Energy Current Through an Area dA into the Solid Angle $d\Omega$	<i>16</i>
2.1.3	Radiation from a Spherical Surface into the Solid Angle $d\Omega$	<i>19</i>
2.1.4	Radiation from a Surface Element into a Hemisphere (Stefan–Boltzmann Radiation Law)	<i>20</i>
2.2	Kirchhoff's Law of Radiation for Nonblack Bodies	<i>22</i>
2.2.1	Absorption by Semiconductors	<i>24</i>
2.3	The Solar Spectrum	<i>24</i>
2.3.1	Air Mass	<i>26</i>
2.4	Concentration of the Solar Radiation	<i>28</i>
2.4.1	The Abbé Sine Condition	<i>29</i>
2.4.2	Geometrical Optics	<i>30</i>
2.4.3	Concentration of Radiation Using the Sine Condition	<i>31</i>
2.5	Maximum Efficiency of Solar Energy Conversion	<i>33</i>
2.6	Problems	<i>39</i>
3	Semiconductors	<i>41</i>
3.1	Electrons in Semiconductors	<i>42</i>
3.1.1	Distribution Function for Electrons	<i>43</i>
3.1.2	Density of States $D_e(\epsilon_e)$ for Electrons	<i>43</i>

3.1.3	Density of Electrons	48
3.2	Holes	50
3.3	Doping	52
3.4	Quasi-Fermi Distributions	57
3.4.1	Fermi Energy and Electrochemical Potential	59
3.4.2	Work Function	63
3.5	Generation of Electrons and Holes	65
3.5.1	Absorption of Photons	65
3.5.2	Generation of Electron–Hole Pairs	69
3.6	Recombination of Electrons and Holes	71
3.6.1	Radiative Recombination, Emission of Photons	72
3.6.2	Nonradiative Recombination	74
3.6.3	Lifetimes	85
3.7	Light Emission by Semiconductors	87
3.7.1	Transition Rates and Absorption Coefficient	88
3.8	Problems	92
4	Conversion of Thermal Radiation into Chemical Energy	95
4.1	Maximum Efficiency for the Production of Chemical Energy	98
4.2	Shockley–Queisser Limit	103
4.3	Problems	104
5	Conversion of Chemical Energy into Electrical Energy	105
5.1	Transport of Electrons and Holes	105
5.1.1	Field Current	106
5.1.2	Diffusion Current	107
5.1.3	Total Charge Current	109
5.2	Separation of Electrons and Holes	111
5.3	Diffusion Length of Minority Carriers	113
5.4	Dielectric Relaxation	115
5.5	Ambipolar Diffusion	116
5.6	Dember Effect	117
5.7	Mathematical Description	120
5.8	Problems	120
6	Basic Structure of Solar Cells	123
6.1	A Chemical Solar Cell	123
6.2	Basic Mechanisms in Solar Cells	128
6.3	Dye Solar Cell	131
6.4	The pn-Junction	133
6.4.1	Electrochemical Equilibrium of Electrons in a pn-Junction in the Dark	133
6.4.2	Potential Distribution across a pn-Junction	134
6.4.3	Current–Voltage Characteristic of the pn-Junction	138
6.5	pn-Junction with Impurity Recombination, Two-Diode Model	143

6.6	Heterojunctions	147
6.7	Semiconductor–Metal Contact	150
6.7.1	Schottky Contact	152
6.7.2	MIS Contact	153
6.8	The Role of the Electric Field in Solar Cells	154
6.9	Organic Solar Cells	160
6.9.1	Excitons	160
6.9.2	Structure of Organic Solar Cells	163
6.10	Light Emitting Diodes (LED)	167
6.11	Problems	169
7	Limitations on Energy Conversion in Solar Cells	171
7.1	Maximum Efficiency of Solar Cells	171
7.2	Efficiency of Solar Cells as a Function of Their Energy Gap	174
7.3	The Optimal Silicon Solar Cell	175
7.3.1	Light Trapping	176
7.4	Thin-film Solar Cells	181
7.4.1	Minimal Thickness of a Solar Cell	182
7.5	Equivalent Circuit	183
7.6	Temperature Dependence of the Open-circuit Voltage	185
7.7	Intensity Dependence of the Efficiency	186
7.8	Efficiencies of the Individual Energy Conversion Processes	186
7.9	Problems	188
8	Concepts for Improving the Efficiency of Solar Cells	189
8.1	Tandem Cells	189
8.1.1	The Electrical Interconnection of Tandem Cells	193
8.2	Concentrator Cells	194
8.3	Thermophovoltaic Energy Conversion	196
8.4	Impact Ionization	197
8.4.1	Hot Electrons from Impact Ionization	200
8.4.2	Energy Conversion with Hot Electrons and Holes	200
8.5	Two-step Excitation in Three-level Systems	203
8.5.1	Impurity Photovoltaic Effect	203
8.5.2	Up- and Down-conversion of Photons	208
8.6	Problems	211
9	Characterization of Solar Cells	213
9.1	Spectral Response and Quantum Efficiency	213
9.2	Quasi-Steady-State Photoconductance	218
9.3	Luminescence	220
9.3.1	Homogeneous Distribution of Electrons and Holes	221
9.3.2	Inhomogeneous Distribution of Electrons and Holes	222
9.3.3	Electroluminescence	223
9.3.4	Photoluminescence	224

9.3.5	Diffusion Length	225
9.3.6	Series Resistance	228
9.4	Thermography	229
9.5	Light-Beam-Induced Current (LBIC)	230
9.6	The Suns- V_{OC} Method	233
9.7	Transient Techniques	237
9.7.1	Photovoltage Decay	237
9.7.2	Transient Absorption	238
9.7.3	Charge Carrier Extraction	240
9.7.4	CELIV – Charge Extraction by Linearly Increasing Voltage	241
9.7.5	Impedance Spectroscopy	241

Solutions 245

Appendix 263

References 267

Index 271