Peter Würfel

Physics of Solar Cells

From Basic Principles to Advanced Concepts

2nd, updated and expanded edition

Problems and Solutions by Uli Würfel

WILEY-VCH Verlag GmbH & Co. KGaA
Contents

List of Symbols  IX

Preface  XI

1  Problems of the Energy Economy  1
   1.1 Energy Economy  1
   1.2 Estimate of the Maximum Reserves of Fossil Energy  4
   1.3 The Greenhouse Effect  6
      1.3.1 Combustion  6
      1.3.2 The Temperature of the Earth  7
   1.4 Problems  9

2  Photons  11
   2.1 Black-body Radiation  11
      2.1.1 Photon Density $n_\nu$ in a Cavity (Planck's Law of Radiation)  12
      2.1.2 Energy Current Through an Area $dA$ into the Solid Angle $d\Omega$  16
      2.1.3 Radiation from a Spherical Surface into the Solid Angle $d\Omega$  19
      2.1.4 Radiation from a Surface Element into a Hemisphere
         (Stefan–Boltzmann Radiation Law)  20
   2.2 Kirchhoff's Law of Radiation for Nonblack Bodies  22
      2.2.1 Absorption by Semiconductors  24
   2.3 The Solar Spectrum  25
      2.3.1 Air Mass  26
   2.4 Concentration of the Solar Radiation  28
      2.4.1 The Abbé Sine Condition  29
      2.4.2 Geometrical Optics  30
      2.4.3 Concentration of Radiation Using the Sine Condition  32
   2.5 Maximum Efficiency of Solar Energy Conversion  33
   2.6 Problems  40
3  **Semiconductors**  43
3.1  Electrons in Semiconductors  44
3.1.1  Distribution Function for Electrons  45
3.1.2  Density of States \(D_e(\varepsilon_e)\) for Electrons  45
3.1.3  Density of Electrons  50
3.2  Holes  52
3.3  Doping  55
3.4  Quasi-Fermi Distributions  59
3.4.1  Fermi Energy and Electrochemical Potential  61
3.4.2  Work Function  66
3.5  Generation of Electrons and Holes  67
3.5.1  Absorption of Photons  67
3.5.2  Generation of Electron–Hole Pairs  71
3.6  Recombination of Electrons and Holes  74
3.6.1  Radiative Recombination, Emission of Photons  74
3.6.2  Nonradiative Recombination  77
3.6.3  Lifetimes  87
3.7  Light Emission by Semiconductors  90
3.7.1  Transition Rates and Absorption Coefficient  90
3.8  Problems  95

4  **Conversion of Thermal Radiation into Chemical Energy**  97
4.1  Maximum Efficiency for the Production of Chemical Energy  100
4.2  Problems  105

5  **Conversion of Chemical Energy into Electrical Energy**  107
5.1  Transport of Electrons and Holes  107
5.1.1  Field Current  108
5.1.2  Diffusion Current  109
5.1.3  Total Charge Current  111
5.2  Separation of Electrons and Holes  113
5.3  Diffusion Length of Minority Carriers  115
5.4  Dielectric Relaxation  117
5.5  Ambipolar Diffusion  118
5.6  Dember Effect  119
5.7  Mathematical Description  122
5.8  Problems  123

6  **Basic Structure of Solar Cells**  125
6.1  A Chemical Solar Cell  125
6.2  Basic Mechanisms in Solar Cells  129
6.3  Dye Solar Cell  131
6.4  The pn-Junction  132
Contents

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 137
6.5 pn-Junction with Impurity Recombination, Two-diode Model 143
6.6 Heterojunctions 145
6.7 Semiconductor-Metal Contact 148
6.7.1 Schottky Contact 150
6.7.2 MIS Contact 151
6.8 The Role of the Electric Field in Solar Cells 151
6.9 Organic Solar Cells 155
6.9.1 Excitons 156
6.9.2 Structure of Organic Solar Cells 159
6.10 Light Emitting Diodes (LED) 163
6.11 Problems 164

7 Limitations on Energy Conversion in Solar Cells 167
7.1 Maximum Efficiency of Solar Cells 167
7.2 Efficiency of Solar Cells as a Function of Their Energy Gap 170
7.3 The Optimal Silicon Solar Cell 172
7.3.1 Light Trapping 173
7.4 Thin-film Solar Cells 178
7.4.1 Minimal Thickness of a Solar Cell 179
7.5 Equivalent Circuit 180
7.6 Temperature Dependence of the Open-circuit Voltage 181
7.7 Intensity Dependence of the Efficiency 182
7.8 Efficiencies of the Individual Energy Conversion Processes 183
7.9 Problems 185

8 Concepts for Improving the Efficiency of Solar Cells 187
8.1 Tandem Cells 187
8.1.1 The Electrical Interconnection of Tandem Cells 191
8.2 Concentrator Cells 192
8.3 Thermophotovoltaic Energy Conversion 194
8.4 Impact Ionization 195
8.4.1 Hot Electrons from Impact Ionization 198
8.4.2 Energy Conversion with Hot Electrons and Holes 198
8.5 Two-step Excitation in Three-level Systems 201
8.5.1 Impurity Photovoltaic Effect 202
8.5.2 Up- and Down-conversion of Photons 206
8.6 Problems 209
VIII | Contents

Prospects for the Future  211

Solutions  215

Appendix  235

References  239

Index  241