

using crystalline silicon and gallium arsenide cells as examples. Chapter 8 deals with thin film photovoltaic materials, discussing physical processes and design issues relevant to thin films and focusing on the ways in which the standard model must be adapted for thin film devices. Chapter 9 deals with various techniques for managing light in order to maximise performance, and Chapter 10 covers a range of approaches, mainly theoretical, to increasing the efficiency of solar cells above the limit for a single band gap photoconverter.

I am grateful to all of the people who have helped me prepare this book. In particular, to Keith Barnham for passing the original proposal from Imperial College Press in my direction; to Leon Freris and David Infield for giving me the opportunity to teach the physics of solar cells to MSc students at Loughborough, and so establish the basic course from which this book developed; to all the research students in photovoltaics at Imperial College for raising so many interesting questions, especially Jenny Barnes, James Connolly and Benjamin Kluftinger; to Ralph Gottshalg, Tom Markvart and Peter Wuerfel for help with questions related to material in this book; to Ned Ekins-Daukes and Jane Nelson for their helpful comments on the text; to Clare Nelson for the cover illustration and to all other colleagues who have helped in my endeavours to understand how these things work, in particular to Richard Corkish, James Durrant, Michael Grätzel, Martin Green, Christiana Honsberg, Stefan Kettemann and Ellen Moons. I am grateful to the Greenpeace Environmental Trust for funding me to study solar cells before they were popular, and to the UK Engineering and Physical Sciences Research Council and for an Advanced Research Fellowship which allowed me to spend my Saturday afternoons writing chapters instead of lectures. Finally I am grateful to John Navas for his encouragement to start on this project and to Laurent Chaminade and his staff at IC Press and to Lakshmi Narayan and colleagues at World Scientific, for their help in seeing it through.

This book is dedicated to the memory of Stephen Robinson and M.V. McCaughan.

Jenny Nelson
London, April 2002

Contents

Preface	v
Chapter 1 Introduction	1
1.1. Photons In, Electrons Out: The Photovoltaic Effect	1
1.2. Brief History of the Solar Cell	2
1.3. Photovoltaic Cells and Power Generation	4
1.3.1. Photovoltaic cells, modules and systems	4
1.3.2. Some important definitions	6
1.4. Characteristics of the Photovoltaic Cell: A Summary	7
1.4.1. Photocurrent and quantum efficiency	7
1.4.2. Dark current and open circuit voltage	9
1.4.3. Efficiency	11
1.4.4. Parasitic resistances	13
1.4.5. Non-ideal diode behaviour	15
1.5. Summary	15
References	16
Chapter 2 Photons In, Electrons Out: Basic Principles of PV	17
2.1. Introduction	17
2.2. The Solar Resource	17
2.3. Types of Solar Energy Converter	22
2.4. Detailed Balance	24
2.4.1. In equilibrium	24
2.4.2. Under illumination	26
2.5. Work Available from a Photovoltaic Device	28
2.5.1. Photocurrent	28

2.5.2.	Dark current	30
2.5.3.	Limiting efficiency	31
2.5.4.	Effect of band gap	33
2.5.5.	Effect of spectrum on efficiency	34
2.6.	Requirements for the Ideal Photoconverter	35
2.7.	Summary	38
	References	39
	Chapter 3 Electrons and Holes in Semiconductors	41
3.1.	Introduction	41
3.2.	Basic Concepts	42
3.2.1.	Bonds and bands in crystals	42
3.2.2.	Electrons, holes and conductivity	44
3.3.	Electron States in Semiconductors	46
3.3.1.	Band structure	46
3.3.2.	Conduction band	48
3.3.3.	Valence band	49
3.3.4.	Direct and indirect band gaps	50
3.3.5.	Density of states	51
3.3.6.	Electron distribution function	54
3.3.7.	Electron and hole currents	55
3.4.	Semiconductor in Equilibrium	56
3.4.1.	Fermi Dirac statistics	56
3.4.2.	Electron and hole densities in equilibrium	57
3.4.3.	Boltzmann approximation	58
3.4.4.	Electron and hole currents in equilibrium	60
3.5.	Impurities and Doping	61
3.5.1.	Intrinsic semiconductors	61
3.5.2.	<i>n</i> type doping	62
3.5.3.	<i>p</i> type doping	63
3.5.4.	Effects of heavy doping	65
3.5.5.	Imperfect and amorphous crystals	65
3.6.	Semiconductor under Bias	66
3.6.1.	Quasi thermal equilibrium	66
3.6.2.	Electron and hole densities under bias	68
3.6.3.	Current densities under bias	69
3.7.	Drift and Diffusion	72
3.7.1.	Current equations in terms of drift and diffusion	72
3.7.2.	Validity of the drift-diffusion equations	75

3.7.3.	Current equations for non-crystalline solids	76
3.8.	Summary	77
	Chapter 4 Generation and Recombination	79
4.1.	Introduction: Semiconductor Transport Equations	79
4.2.	Generation and Recombination	81
4.3.	Quantum Mechanical Description of Transition Rates	83
4.3.1.	Fermi's Golden Rule	83
4.3.2.	Optical processes in a two level system	85
4.4.	Photogeneration	87
4.4.1.	Photogeneration rate	88
4.4.2.	Thermalisation	89
4.4.3.	Microscopic description of absorption	90
4.4.4.	Direct gap semiconductors	93
4.4.5.	Indirect gap semiconductors	94
4.4.6.	Other types of behaviour	96
4.4.7.	Examples and data	98
4.5.	Recombination	99
4.5.1.	Types of recombination	99
4.5.2.	Radiative recombination	99
4.5.3.	Simplified expressions for radiative recombination	102
4.5.4.	Auger recombination	105
4.5.5.	Shockley Read Hall recombination	106
4.5.6.	Surface and grain boundary recombination	110
4.5.7.	Traps versus recombination centres	111
4.6.	Formulation of the Transport Problem	112
4.6.1.	Comments on the transport problem	113
4.6.2.	Transport equations in a crystal	114
4.7.	Summary	115
	References	117
	Chapter 5 Junctions	119
5.1.	Introduction	119
5.2.	Origin of Photovoltaic Action	120
5.3.	Work Function and Types of Junction	124
5.4.	Metal–Semiconductor Junction	125
5.4.1.	Establishing a field	125
5.4.2.	Behaviour in the light	126
5.4.3.	Behaviour in the dark	127

5.4.4.	Ohmic contacts	129
5.4.5.	Limitations of the Schottky barrier junction	130
5.5.	Semiconductor-Semiconductor Junctions	131
5.5.1.	<i>p-n</i> junction	131
5.5.2.	<i>p-i-n</i> junction	132
5.5.3.	<i>p-n</i> heterojunction	133
5.6.	Electrochemical Junction	133
5.7.	Junctions in Organic Materials	137
5.8.	Surface and Interface States	139
5.8.1.	Surface states on free surfaces	139
5.8.2.	Effect of interface states on junctions	141
5.9.	Summary	143
	References	144

Chapter 6 Analysis of the *p-n* Junction 145

6.1.	Introduction	145
6.2.	The <i>p-n</i> Junction	146
6.2.1.	Formation of <i>p-n</i> junction	146
6.2.2.	Outline of approach	147
6.3.	Depletion Approximation	149
6.3.1.	Calculation of depletion width	150
6.4.	Calculation of Carrier and Current Densities	152
6.4.1.	Currents and carrier densities in the neutral regions	152
6.4.2.	Currents and carrier densities in the space charge region	154
6.4.3.	Total current density	156
6.5.	General Solution for $J(V)$	156
6.6.	<i>p-n</i> Junction in the Dark	160
6.6.1.	At equilibrium	160
6.6.2.	Under applied bias	160
6.7.	<i>p-n</i> Junction under Illumination	165
6.7.1.	Short circuit	165
6.7.2.	Photocurrent and QE in special cases	167
6.7.3.	<i>p-n</i> junction as a photovoltaic cell	169
6.8.	Effects on <i>p-n</i> Junction Characteristics	172
6.8.1.	Effects of parasitic resistances	172
6.8.2.	Effect of irradiation	172
6.8.3.	Effect of temperature	173

6.8.4.	Other device structures	174
6.8.5.	Validity of the approximations	174
6.9.	Summary	175
	References	176

Chapter 7 Monocrystalline Solar Cells 177

7.1.	Introduction: Principles of Cell Design	177
7.2.	Material and Design Issues	178
7.2.1.	Material dependent factors	178
7.2.2.	Design factors	179
7.2.3.	General design features of <i>p-n</i> junction cells	180
7.3.	Silicon Material Properties	180
7.3.1.	Band structure and optical absorption	180
7.3.2.	Doping	181
7.3.3.	Recombination	182
7.3.4.	Carrier transport	185
7.4.	Silicon Solar Cell Design	186
7.4.1.	Basic silicon solar cell	186
7.4.2.	Cell fabrication	186
7.4.3.	Optimisation of silicon solar cell design	188
7.4.4.	Strategies to enhance absorption	190
7.4.5.	Strategies to reduce surface recombination	191
7.4.6.	Strategies to reduce series resistance	194
7.4.7.	Evolution of silicon solar cell design	194
7.4.8.	Future directions in silicon cell design	197
7.4.9.	Alternatives to silicon	198
7.5.	III-V Semiconductor Material Properties	198
7.5.1.	III-V semiconductor band structure and optical absorption	198
7.5.2.	Gallium arsenide	200
7.5.3.	Doping	201
7.5.4.	Recombination	202
7.5.5.	Carrier transport	203
7.5.6.	Reflectivity	203
7.6.	GaAs Solar Cell Design	204
7.6.1.	Basic GaAs solar cell	204
7.6.2.	Optimisation of GaAs solar cell design	204
7.6.3.	Strategies to reduce front surface recombination	205
7.6.4.	Strategies to reduce series resistance	207

7.6.5. Strategies to reduce substrate cost	208
7.7. Summary	208
References	210
Chapter 8 Thin Film Solar Cells	211
8.1. Introduction	211
8.2. Thin Film Photovoltaic Materials	213
8.2.1. Requirements for suitable materials	213
8.3. Amorphous Silicon	213
8.3.1. Materials properties	213
8.3.2. Defects in amorphous material	215
8.3.3. Absorption	217
8.3.4. Doping	217
8.3.5. Transport	219
8.3.6. Stability	220
8.3.7. Related alloys	221
8.4. Amorphous Silicon Solar Cell Design	221
8.4.1. Amorphous silicon $p-i-n$ structures	221
8.4.2. $p-i-n$ solar cell device physics	222
8.4.3. Fabrication of a-Si solar cells	227
8.4.4. Strategies to improve a-Si cell performance	227
8.5. Defects in Polycrystalline Thin Film Materials	229
8.5.1. Grain boundaries	230
8.5.2. Effects of grain boundaries on transport	233
8.5.3. Depletion approximation model for grain boundary	234
8.5.4. Majority carrier transport	236
8.5.5. Effect of illumination	239
8.5.6. Minority carrier transport	240
8.5.7. Effects of grain boundary recombination on solar cell performance	242
8.6. CuInSe ₂ Thin Film Solar Cells	243
8.6.1. Materials properties	243
8.6.2. Heterojunctions in thin film solar cell design	244
8.6.3. CuInGaSe ₂ solar cell design	245
8.7. CdTe Thin Film Solar Cells	246
8.7.1. Materials properties	246
8.7.2. CdTe solar cell design	247
8.8. Thin Film Silicon Solar Cells	248

8.8.1. Materials properties	248
8.8.2. Microcrystalline silicon solar cell design	248
8.9. Summary	249
References	251
Chapter 9 Managing Light	253
9.1. Introduction	253
9.2. Photon Flux: A Review and Overview of Light Management	255
9.2.1. Routes to higher photon flux	257
9.3. Minimising Reflection	258
9.3.1. Optical properties of semiconductors	258
9.3.2. Antireflection coatings	260
9.4. Concentration	263
9.4.1. Limits to concentration	263
9.4.2. Practical concentrators	264
9.5. Effects of Concentration on Device Physics	266
9.5.1. Low injection	266
9.5.2. High injection	267
9.5.3. Limits to efficiency under concentration	269
9.5.4. Temperature	270
9.5.5. Series resistance	270
9.5.6. Concentrator cell design	270
9.5.7. Concentrator cell materials	271
9.6. Light Confinement	272
9.6.1. Light paths and ray tracing	272
9.6.2. Mirrors	274
9.6.3. Randomising surfaces	275
9.6.4. Textured surfaces	276
9.6.5. Practical schemes	278
9.6.6. Light confining structures: restricted acceptance areas and external cavities	280
9.6.7. Effects of light trapping on device physics	281
9.7. Photon Recycling	282
9.7.1. Theory of photon recycling	282
9.7.2. Practical schemes	285
9.8. Summary	286
References	288