

# Contents

<b>Abstract</b>	<b>1</b>
<b>Zusammenfassung</b>	<b>5</b>
<b>1 Introduction</b>	<b>9</b>
<b>2 Fundamentals</b>	<b>13</b>
2.1 The principle of detailed balance . . . . .	13
2.2 The Shockley-Queisser limit . . . . .	14
2.3 Combining transport with detailed balance . . . . .	18
2.3.1 A two state solar cell model . . . . .	18
2.3.2 The one sided pn-junction . . . . .	21
2.3.3 Radiative limit for arbitrary mobilities . . . . .	23
2.4 Solar cell and light emitting diode . . . . .	24
2.5 Properties of optoelectronic devices - a brief summary . . . . .	26
<b>3 Detailed balance model for bipolar charge transport</b>	<b>31</b>
3.1 Introduction . . . . .	31
3.2 pn and pin type solar cells . . . . .	33
3.3 Superposition, ideality and reciprocity in pin-type solar cells . . . . .	37
3.4 Model . . . . .	41
3.5 Application to quantum well solar cells . . . . .	43
3.5.1 Introduction . . . . .	43
3.5.2 Optical results . . . . .	45
3.5.3 Results for finite mobilities . . . . .	50
3.5.4 Results for non-radiative recombination . . . . .	54

3.5.5	Tandem solar cells . . . . .	58
3.5.6	Conclusions . . . . .	60
<b>4</b>	<b>Detailed balance model for excitonic and bipolar charge transport</b>	<b>63</b>
4.1	Introduction . . . . .	63
4.2	Model . . . . .	64
4.2.1	Excitonic and bipolar solar cells . . . . .	64
4.2.2	pn-type and pin-type solar cells . . . . .	68
4.3	Results . . . . .	69
4.3.1	Excitonic and bipolar photocurrent . . . . .	69
4.3.2	Current/voltage curves . . . . .	72
4.3.3	Electroluminescence and quantum efficiency . . . . .	76
<b>5</b>	<b>Detailed balance model for bulk heterojunction solar cells</b>	<b>81</b>
5.1	Introduction . . . . .	81
5.2	Model . . . . .	83
5.2.1	Charge separation scheme . . . . .	83
5.2.2	Differential equations for free carriers . . . . .	83
5.2.3	Balance equation for bound carriers . . . . .	84
5.2.4	Differential equation for excitons . . . . .	87
5.2.5	Effective generation and recombination rates . . . . .	89
5.2.6	Equilibrium concentration of excitons . . . . .	90
5.2.7	Comparison with the model of Koster et al. . . . .	91
5.3	Fundamental aspects . . . . .	92
5.3.1	Influence of the carrier mobilities and the surface recombination velocity . . . . .	92
5.3.2	Influence of exciton diffusion on the photocurrent . . . . .	96
5.3.3	The role of band offsets . . . . .	96
5.3.4	The role of the blend morphology . . . . .	99
5.3.5	Optoelectronic reciprocity . . . . .	101
5.4	Comparison to experimental results . . . . .	106

<b>6 Detailed balance model for solar cells with multiple exciton generation</b>	<b>111</b>
6.1 Introduction . . . . .	111
6.2 Model . . . . .	112
6.3 Generation of multiexcitons . . . . .	116
6.4 Results . . . . .	119
6.5 Summary . . . . .	120
<b>7 Experimental applications of the reciprocity relation</b>	<b>123</b>
7.1 Introduction . . . . .	123
7.2 Crystalline Silicon . . . . .	125
7.2.1 Spectrally resolved EL . . . . .	125
7.2.2 Spatially resolved EL . . . . .	129
7.2.3 Interpretation of EL images taken with filters . . . . .	134
7.2.4 Absolute EL emission and the LED quantum efficiency . . . . .	147
7.3 Cu(In,Ga)Se <sub>2</sub> . . . . .	149
7.3.1 Introduction . . . . .	149
7.3.2 Experiments . . . . .	150
7.3.3 Temperature dependent measurements . . . . .	151
7.3.4 Reciprocity between electroluminescence and photovoltaic quantum efficiency . . . . .	162
7.3.5 Summary . . . . .	166
7.4 GaInP/GaInAs/Ge-multijunction solar cells . . . . .	167
<b>8 Conclusions and Outlook</b>	<b>173</b>
<b>A List of Publications</b>	<b>177</b>
A.1 Publications in Journals . . . . .	177
A.2 Peer reviewed conference proceedings . . . . .	178
A.3 Conference proceedings (not reviewed) . . . . .	179
<b>B Curriculum vitae</b>	<b>181</b>
<b>Bibliography</b>	<b>182</b>

