

Contents

1	Preamble	1
1.1	The Imperative of Renewable Energy	1
1.2	Photovoltaic Energy Conversion	1
1.3	Subject of This Work	2
1.4	Outline	3
	References	4
2	Introduction to Solar Cell Operation	7
2.1	Doped Semiconductors	7
2.1.1	The Band Gap	7
2.1.2	Classification of Semiconductors	8
2.1.3	Interaction with Light—Indirect Semiconductors	9
2.1.4	Doping	9
2.2	Quasi-Fermi Energy—Electrochemical Potential	10
2.2.1	Quasi-Fermi Levels	11
2.2.2	The Electrochemical Potential	12
2.3	The pn-Junction	13
2.3.1	Dark pn-Junction	14
2.3.2	Illuminated pn-Junction	15
2.3.3	Charge Current of a pn-Junction	16
2.4	Solar Cell Efficiency—Loss Mechanisms	19
2.4.1	Idealized Reversible Conversion Process	19
2.4.2	Single Junction-Detailed Balance Limit	20
2.4.3	Classification of Power Losses	21
2.5	Carrier Recombination and Transport	22
2.5.1	Recombination	22
2.5.2	Transport	23
	References	23
3	Dynamics of Charge Carriers	25
3.1	The Continuity Equation	25
3.1.1	Recombination Lifetime	25

3.1.2	Motivation of the Continuity Equation	31
3.1.3	Boundary Conditions: Interface Recombination	33
3.1.4	Effective Carrier Lifetime	34
3.1.5	Ambipolar Diffusion	40
3.1.6	Trapping	41
3.2	Solutions of the Continuity Equation	48
3.2.1	Excess Carrier Generation Rate	48
3.2.2	Ordinary Steady-State Solution	50
3.2.3	Ordinary Harmonically Modulated Solution	53
3.2.4	Full Harmonically Modulated Solutions	56
	References	60
4	Luminescence of Silicon	65
4.1	The Generalized Law of Radiation	65
4.1.1	Detailed Balance and Derivative Considerations	65
4.1.2	Transition Rates According to Würfel	66
4.1.3	Photon Density	68
4.1.4	The Generalized Planck Law of Radiation	69
4.1.5	Application to Indirect Semiconductors	69
4.2	Electronic Properties from Luminescence	71
4.2.1	From Spontaneous Emission to Excess Carrier Density	71
4.2.2	The Coefficient of Radiative Recombination	72
4.2.3	Measured Luminescence Intensity	73
4.2.4	Dynamic Luminescence Intensity	75
4.3	Classification of Luminescence Applications	77
4.3.1	The Ab Initio Class	77
4.3.2	The Ratio Class	78
4.3.3	The Dynamic Class	79
	References	80
5	Harmonically Modulated Lifetime	85
5.1	Quasi-Steady-State Measurement Conditions	85
5.1.1	Definition of Dynamic Regimes	85
5.1.2	The Benefit of Quasi-Steady-State	87
5.1.3	Quasi-Steady-State Perceptions	88
5.2	Self-Consistency of the Continuity Equation	89
5.2.1	The Principle of Self-Consistency	89
5.2.2	Self-Consistency and Phase Information	91
5.2.3	Essential Properties of Self-Consistent Lifetime	93
	References	98
6	Constraints of Dynamic Carrier Lifetime Techniques	99
6.1	Nonuniform Generation and Recombination	99

6.1.1	Harmonical Modulation: Dynamic or Steady-State	100
6.1.2	Harmonically Modulated Weighting of Decay Modes . . .	102
6.1.3	On the Interpretation of Modulated Lifetime	110
6.2	Differential Lifetime	112
6.2.1	Previous Findings on Differential Lifetime.	112
6.2.2	Theory of Light-Biased Decay Time	113
6.2.3	Implications of the Theory of Light-Biased Decay Time	116
6.2.4	Numerical Validation	120
	References	124
7	Evolution of the Experimental Setup	127
7.1	Harmonically Modulated Luminescence Setup	127
7.1.1	Data Acquisition and Software	127
7.1.2	Light Sources	129
7.1.3	Filters—Optics—Apertures.	129
7.1.4	Detectors and Amplifiers	132
7.2	Microsecond Lifetimes.	132
7.2.1	Signal Synchronization	133
7.2.2	Attenuation of Nonluminescent Light	138
7.3	Carrier Lifetimes of Metalized Substrates.	141
7.3.1	Modifications of Setup and Analysis.	142
7.3.2	Experimental Evidence of Equivalent Accuracy	144
7.3.3	Discussion of Limitations.	145
7.4	Dynamic Electroluminescence.	145
7.4.1	Experimental Setup Modifications.	146
7.4.2	Experimental Proof of Concept.	148
7.4.3	Discussion of Limitations.	148
	References	150
8	Conceptual Advances: Recombination Properties	153
8.1	Phase-Sensitive Carrier Lifetime Approaches	153
8.1.1	Self-Consistency and Net Dopant Concentration.	153
8.1.2	The Peak Shift Approach.	155
8.1.3	The Self-Sufficient Approach.	157
8.1.4	The $d2a$ Approach	162
8.2	Broad Range Injection-Dependent Lifetime	165
8.2.1	Combined Modulated and Steady-State Approach.	166
8.2.2	Fluctuation of Dark Photocurrent	167
8.2.3	Data Corrections.	169
8.2.4	Experimental Results.	172
8.3	Lifetimes from Photoluminescence Images	173
8.3.1	Requirements and Constraints for Accurate Lifetimes . . .	174

8.3.2	Derivation of Averaging Procedure	175
8.3.3	Experimental Results	181
8.3.4	Discussion of Limitations	186
8.4	Recombination Properties of Silicon Ingots	187
8.4.1	Review of Relevant Facts and Literature	188
8.4.2	Combined Access to Recombination and Diffusion	188
8.4.3	Experimental Results	194
	References	197
9	Conceptual Advances: Transport Properties	203
9.1	Net Dopant Concentration	203
9.1.1	Review of Relevant Facts and Literature	203
9.1.2	Net Dopant Concentration via Modulated Luminescence	205
9.1.3	Experimental Results	210
9.1.4	Discussion of Limitations	213
9.2	Minority Carrier Mobility	215
9.2.1	Review of Relevant Facts and Literature	215
9.2.2	Experimental Design	217
9.2.3	Modulated Lifetime Versus Steady-State Lifetime	219
9.2.4	Considerations for Broad Applicability and Accuracy	221
9.2.5	Experimental Results for p-Type Silicon	224
	References	228
10	Summary and Outlook	233
10.1	Summary of Advances	233
10.1.1	Theoretical Advances	233
10.1.2	Conceptual Advances	233
10.1.3	Experimental Advances	234
10.2	Outlook	235
10.2.1	Pending Investigations	235
10.2.2	Derivative Applications and Novel Pathways	236
	References	236
	Appendix A: Miscellaneous	237
	Appendix B: Reassessment of the Radial Sensitivity of QSSPC	251
	Appendix C: Comparative Analysis of QSSPC and Modulated Luminescence	259
	Appendix D: Absorption Coefficient Measurement	275
	Appendix E: Impact of Non-Planar Interfaces on Recombination Measurements	279
	Publications Related to this Dissertation	283

Quantitative Recombination and Transport Properties in
Silicon from Dynamic Luminescence

Giesecke, J.

2014, XXI, 284 p. 86 illus., 63 illus. in color., Hardcover

ISBN: 978-3-319-06156-6