

Contents

Series Preface	xiii
Preface	xv
1 Epitaxial Thin Film Crystalline Silicon Solar Cells on Low Cost Silicon Carriers	1
Jef Poortmans	
1.1 Introduction	1
1.2 Deposition Technologies	4
1.2.1 Thermally Assisted Chemical Vapor Deposition	5
1.2.2 Liquid Phase Epitaxy – Electrodeposition	6
1.2.3 Close Space Vapor Transport Technique	8
1.2.4 Ion Assisted Deposition	9
1.2.5 Low Energy Plasma Enhanced Chemical Vapor Deposition/Electron Cyclotron Resonance Chemical Vapor Deposition	10
1.3 Silicon Based Epitaxial Layer Structures for Increased Absorbance	11
1.3.1 Epitaxial Growth on Textured Substrates	11
1.3.2 Silicon–Germanium Alloys	12
1.3.3 Germanium–Silicon Structures	15
1.3.4 Epitaxial Layers on a Buried Backside Reflector	17
1.4 Epitaxial Solar Cell Results and Analysis	21
1.4.1 Laboratory Type Epitaxial Solar Cells	21
1.4.2 Industrial Epitaxial Solar Cells	22
1.4.3 Special Epitaxial Solar Cell Structures	24
1.5 High Throughput Silicon Deposition	24
1.5.1 Chemical Vapor Deposition Reactor Upscaling	25
1.5.2 Liquid Phase Epitaxy Reactor Upscaling	29
1.6 Conclusions	32
References	32
2 Crystalline Silicon Thin Film Solar Cells on Foreign Substrates by High Temperature Deposition and Recrystallization	39
Stefan Reber, Thomas Kieliba, Sandra Bau	
2.1 Motivation and Introduction to Solar Cell Concept	39
2.2 Substrate and Intermediate Layer	42

viii CONTENTS

2.2.1 Substrate	42
2.2.2 Intermediate Layer	44
2.3 Zone Melting Recrystallization	48
2.3.1 Introduction	48
2.3.2 Zone Melting Recrystallization Film Growth	51
2.3.3 Features of Silicon Layers Recrystallized by Zone Melting Recrystallization	53
2.3.4 Development of Lamp Heated Zone Melting Recrystallization Processors	59
2.3.5 Zone Melting Recrystallization on Ceramic Substrates	64
2.4 Silicon Deposition	66
2.4.1 Requirements of Silicon Deposition for Photovoltaics	67
2.4.2 Some Basics on Thermal Silicon Atmospheric Pressure Chemical Vapor Deposition from Chlorosilanes	68
2.4.3 R&D Trends in Silicon Atmospheric Pressure Chemical Vapor Deposition for Photovoltaics	71
2.4.4 Silicon Chemical Vapor Deposition on Ceramic Substrates	73
2.5 Solar Cells on Foreign Substrates	75
2.5.1 Options for Solar Cell Fabrication	76
2.5.2 Solar Cells on Model Substrates	78
2.5.3 Solar Cells on Low Cost Substrates	82
2.6 Summary and Outlook	85
Acknowledgments	87
References	87
3 Thin Film Polycrystalline Silicon Solar Cells	97
Guy Beaucarne, Abdellilah Slaoui	
3.1 Introduction	97
3.1.1 Definition	97
3.1.2 Why Polycrystalline Thin Film Silicon Solar Cells?	98
3.2 Potential of Polysilicon Solar Cells	98
3.2.1 Light Confinement	98
3.2.2 Diffusion Length	99
3.2.3 Modeling	100
3.3 Substrates for Polysilicon Cells	101
3.4 Film Formation	103
3.4.1 Initial Step for Grain Size Enhancement	103
3.4.2 Techniques for Active Layer Formation	106
3.4.3 Defect Density and Activity	112
3.5 Solar Cell and Module Processing	115
3.5.1 Device Structure	115
3.5.2 Junction Formation	117
3.5.3 Defect Passivation	118
3.5.4 Isolation and Interconnection	118
3.6 Polysilicon Solar Cell Technologies	120
3.6.1 Solid Phase Crystallization Heterojunction with Intrinsic Thin Layer Solar Cells	120
3.6.2 Surface Texture and Enhanced Absorption with Back Reflector Solar Cells	121

3.6.3 Crystalline Silicon on Glass Technology	121
3.6.4 Other Research Efforts Around the World	122
3.7 Conclusion	123
References	123
4 Advances in Microcrystalline Silicon Solar Cell Technologies	133
Evelyne Vallat-Sauvain, Arvind Shah and Julien Bailat	
4.1 Introduction	133
4.2 Microcrystalline Silicon: Material Fabrication and Characterization	134
4.2.1 Microcrystalline Silicon Deposition Techniques	134
4.2.2 Undoped Microcrystalline Layers	137
4.2.3 Doped Layers	147
4.3 Microcrystalline Silicon Solar Cells	148
4.3.1 Light Management Issues	149
4.3.2 Single Junction Microcrystalline Silicon Solar Cells	154
4.3.3 Tandem Amorphous/Microcrystalline Silicon Solar Cells: The Micromorph Concept	159
4.4 Conclusions	163
References	165
5 Advanced Amorphous Silicon Solar Cell Technologies	173
Miro Zeman	
5.1 Introduction	173
5.2 Overview of Amorphous Silicon Solar Cell Technology Development and Current Issues	174
5.2.1 1970s	174
5.2.2 1980s	174
5.2.3 1990s	174
5.2.4 After 2000	175
5.2.5 Current Technology Issues	175
5.3 Hydrogenated Amorphous Silicon	177
5.3.1 Atomic Structure	177
5.3.2 Density of States	179
5.3.3 Models for the Density of States and Recombination–Generation Statistics	180
5.3.4 Optical Properties	181
5.3.5 Electrical Properties	183
5.3.6 Determination of Density of States	187
5.3.7 Metastability	190
5.3.8 Hydrogenated Amorphous Silicon from Hydrogen Diluted Silane	192
5.3.9 Doping of Hydrogenated Amorphous Silicon	194
5.3.10 Alloying of Hydrogenated Amorphous Silicon	196
5.4 Deposition of Hydrogenated Amorphous Silicon	197
5.4.1 Radio Frequency Plasma Enhanced Chemical Vapor Deposition	198
5.4.2 Direct Plasma Enhanced Chemical Vapor Deposition Techniques	200
5.4.3 Remote Plasma Enhanced Chemical Vapor Deposition Techniques	202
5.4.4 Hotwire Chemical Vapor Deposition	203

x CONTENTS

5.5 Amorphous Silicon Solar Cells	204
5.5.1 Hydrogenated Amorphous Silicon Solar Cell Structure	204
5.5.2 Hydrogenated Amorphous Silicon Solar Cell Configurations	207
5.5.3 Design Approaches for Highly Efficient Solar Cells	208
5.5.4 Light Trapping and Transparent Conductive Oxides	209
5.5.5 Degradation of Hydrogenated Amorphous Silicon Solar Cells	211
5.5.6 Multijunction Hydrogenated Amorphous Silicon Solar Cells	212
5.6 Performance and Fabrication of Hydrogenated Amorphous Silicon Based Modules	219
5.6.1 Energy Yield	221
5.6.2 Fabrication of Hydrogenated Amorphous Silicon Based Modules	223
5.6.3 Plasma enhanced Chemical Vapor Deposition Systems	223
5.7 Applications	227
5.8 Outlook	229
Acknowledgments	230
References	230
6 Chalcopyrite Based Solar Cells	237
Reiner Klenk, Martha Ch. Lux-Steiner	
6.1 Introduction	237
6.2 Potential of Chalcopyrite Photovoltaic Modules	237
6.3 Technology for the Preparation of Chalcopyrite Solar Cells and Modules	239
6.3.1 Absorber	240
6.3.2 Contacts	244
6.4 Characterization and Modeling	247
6.4.1 Cell Concept	248
6.4.2 Carrier Density and Transport	250
6.4.3 Loss Mechanisms	251
6.5 Scaling Up and Production	254
6.5.1 Cost Estimations	257
6.5.2 Module Performance	258
6.5.3 Sustainability	259
6.6 Developing Future Chalcopyrite Technology	260
6.6.1 Lightweight and Flexible Substrates	260
6.6.2 Cadmium Free Cells	261
6.6.3 Indium Free Absorbers	263
6.6.4 Novel Back Contacts	263
6.6.5 Bifacial Cells and Superstrate Cells	263
6.6.6 Nonvacuum Processing	264
6.6.7 Wide Gap and Tandem Cells	265
References	266
7 Cadmium Telluride Thin Film Solar Cells: Characterization, Fabrication and Modeling	277
Marc Burgelman	
7.1 Introduction	277

CONTENTS xi

7.2 Materials and Cell Concepts for Cadmium Telluride Based Solar Cells	278
7.2.1 Optical Properties of Cadmium Telluride	279
7.2.2 Electrical Properties of Cadmium Telluride	281
7.2.3 The Buffer Material: Cadmium Sulfide	283
7.2.4 Window Materials for Cadmium Telluride Based Solar Cells	285
7.3 Research Areas and Trends in Cadmium Telluride Solar Cells	286
7.3.1 The Activation Treatment of Cadmium Telluride	286
7.3.2 The Back Contact Structure	288
7.3.3 Environmental Issues	290
7.3.4 Other Research Areas and Trends	291
7.4 Fabrication of Cadmium Telluride Cells and Modules	294
7.4.1 Deposition Methods for Cadmium Telluride Based Solar Cells	294
7.4.2 Design of Series Integrated Cadmium Telluride Modules	296
7.4.3 Production of Cadmium Telluride Solar Modules	297
7.5 Advanced Characterization and Modeling of Cadmium Telluride Solar Cells	298
7.5.1 Characterization and Modeling: Introduction	298
7.5.2 Characterization Methods for Cadmium Telluride Materials and Cells	298
7.5.3 Modeling of Thin Film Cadmium Telluride Solar Cells	303
7.6 Conclusions	314
Acknowledgments	314
References	314
8 Charge Carrier Photogeneration in Doped and Blended Organic Semiconductors	325
Vladimir I. Arkhipov, Heinz Bässler	
8.1 Introduction	325
8.2 Exciton Dissociation in Neat and Homogeneously Doped Random Organic Semiconductors	326
8.2.1 Intrinsic Photogeneration in Conjugated Polymers	326
8.2.2 Sensitized Photogeneration of Charge Carriers in Homogeneously Doped Conjugated Polymers	328
8.2.3 Photogeneration of Charge Carriers at a Donor–Acceptor Interface	335
8.3 Models of Exciton Dissociation in Homogeneously Doped Conjugated Polymers and in Polymer Based Donor/Acceptor Blends	349
8.3.1 The Onsager–Braun Model	349
8.3.2 Exciton Dissociation in Conjugated Polymers Homogeneously Doped with Electron Scavengers	351
8.3.3 Exciton Dissociation at a Polymer Donor/Acceptor Interface	353
8.4 Conclusions	357
References	358
9 Nanocrystalline Injection Solar Cells	363
Michael Grätzel	
9.1 Introduction	363
9.2 Band Diagram and Operational Principle of the Dye Sensitized Solar Cell	364

xii CONTENTS

9.3 The Importance of the Nanostructure	365
9.3.1 Light Harvesting by a Sensitizer Monolayer Adsorbed on a Mesoscopic Semiconductor Film	366
9.3.2 Enhanced Red and Near Infrared Response by Light Containment	368
9.3.3 Light Induced Charge Separation and Conversion of Photons to Electric Current	369
9.3.4 Charge Carrier Collection	371
9.3.5 Quantum Dot Sensitizers	374
9.4 Photovoltaic Performance of the Dye Sensitized Solar Cell	375
9.4.1 Photocurrent Action Spectra	375
9.4.2 Overall Conversion Efficiency Under Global AM1.5 Standard Reporting Conditions	376
9.4.3 Increasing the Open Circuit Photovoltage	377
9.5 Development of New Sensitizers and Redox Systems	378
9.6 Solid State Dye Sensitized Solar Cells	379
9.7 Dye Sensitized Solar Cell Stability	379
9.7.1 Criteria for Long Term Stability of the Dye	379
9.7.2 Kinetic Measurements	380
9.7.3 Recent Experimental Results on Dye Sensitized Solar Cell Stability	381
9.7.4 First Large Scale Field Tests and Commercial Developments	382
9.8 Future Prospects	384
Acknowledgments	384
References	384
10 Charge Transport and Recombination in Donor–Acceptor Bulk Heterojunction Solar Cells	387
A. J. Mozer, N. S. Sariciftci	
10.1 Introduction	387
10.2 Development of Bulk Heterojunction Solar Cells	388
10.3 Bulk Heterojunction Solar Cells	391
10.3.1 Operational Principles	391
10.3.2 Nanomorphology–Property Relations	394
10.3.3 Improving the Photon Harvesting	397
10.4 Charge Carrier Mobility and Recombination	399
10.4.1 Measurement Techniques	399
10.4.2 Charge Transport in Conjugated Polymers	401
10.4.3 Charge Transport and Recombination in Bulk Heterojunction Solar Cells	412
10.5 Summary	421
Acknowledgments	421
References	422
11 The Terawatt Challenge for Thin Film Photovoltaics	427
Ken Zweibel	
11.1 Prologue	427
11.2 ‘The Only Big Number Out There – 125 000 TW’ (Quote, Nate Lewis, 2004)	428

CONTENTS **xiii**

11.3 Low Cost and the Idea of Thin Films	431
11.4 A Bottom Up Analysis of Thin Film Module Costs	431
11.4.1 Approach	432
11.4.2 Results	435
11.5 Other Aspects of the ‘Terawatt Challenge’	455
11.6 Risks and Perspective	458
Acknowledgments	459
Appendix 11.1	459
Appendix 11.2	460
References	460
Index	463

