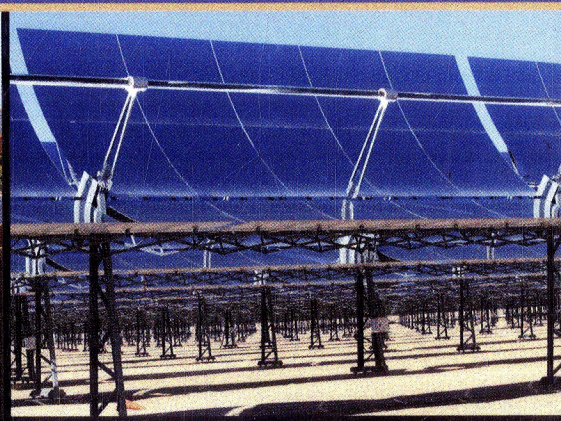
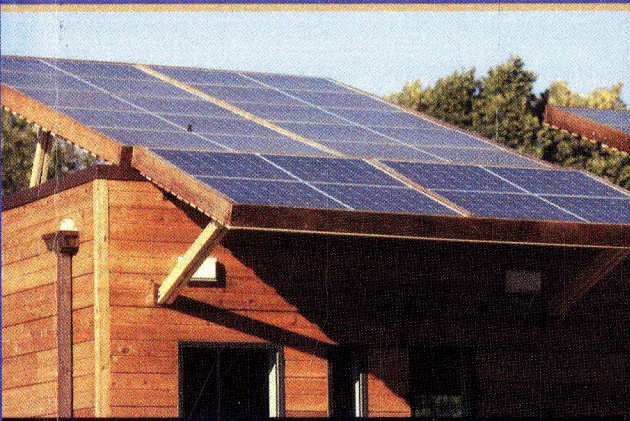


# Solar Cell Technology and Applications

A. R. Jha, Ph.D.



 CRC Press  
Taylor & Francis Group  
AN AUERBACH BOOK

---

# Contents

---

Preface.....	xvii
<b>1 Chronological History and Scientific Advancements in the Development of Solar Cell Technology .....</b>	<b>1</b>
1.1 Introduction .....	1
1.1.1 Chronological History of Developmental and Photovoltaic Power Generation Schemes Worldwide .....	2
1.1.2 Why Solar Energy? .....	4
1.2 Identification of Critical Parameters and Design Aspects of a Silicon Solar Cell.....	4
1.3 Applications of Solar Power Systems.....	6
1.3.1 Solar Power Sources for Homes and Commercial Buildings .....	7
1.3.1.1 Corporate Rooftops Using High Capacity Solar Energy Systems.....	8
1.3.1.2 Solar Module and Panel Installation Requirements.....	9
1.3.1.3 Impact of State and Federal Tax Rebates and Incentives .....	10
1.3.1.4 Photovoltaic (PV) Installation Capacity Worldwide .....	11
1.3.1.5 Factors Impacting Solar Panel Installations .....	12
1.3.2 Photovoltaic Solar Energy Converters for Space Applications.....	13
1.3.3 Radio Relay Stations.....	15
1.3.4 Navigation Aid Sensors.....	15
1.3.5 Railroad Communications Networks .....	16
1.3.6 Educational TV Programs.....	17
1.3.7 Optimization of Solar Electric System for Specific Applications.....	17

1.4	Fabrication Materials for Solar Cells and Panels .....	19
1.4.1	Crystalline Silicon Solar Cells .....	19
1.4.2	Fabrication of a-Si Thin-Film Solar Cells Using Laser Scribing .....	22
1.4.3	Automated In-Line Processing for Thin-Film Solar Cells .....	22
1.4.4	Thin-Film Photovoltaic Market Growth .....	23
1.5	Concentrated Solar Technology .....	25
1.5.1	Collaboration Key to Successful Entrepreneurship .....	27
1.5.2	Low-Cost Concentrator Technique to Intensify the Sunlight .....	28
1.6	Cost Estimates for Solar Modules, Panels, and Systems .....	29
1.7	Solar Cell Performance Degradation and Failure Mechanisms in Solar Modules .....	30
1.7.1	Solar Power Generation Cost Estimates .....	32
1.7.2	Techniques for Optimization of PV Power Systems .....	32
1.7.3	Techniques to Reduce Cell Cost and Improve Efficiency .....	33
1.7.3.1	Low Cost and Efficient Solar Cells .....	33
1.7.3.2	Identification of Low Cost PV Cell Materials .....	35
1.8	Summary .....	36
	References .....	37
<b>2</b>	<b>Design Expressions and Critical Performance Parameters for Solar Cells .....</b>	<b>39</b>
2.1	Introduction .....	39
2.2	Spectral Response of Solar Cell Structure .....	40
2.2.1	Impact of Spectral Response Parameters on Cell Performance .....	41
2.3	Theoretical Model of the Silicon Solar Cell .....	42
2.3.1	Short-Circuit Current .....	43
2.4	Parametric Requirements for Optimum Performance of Solar Cell Devices .....	44
2.4.1	Introduction .....	44
2.4.2	Theory of Spectral Response of p-n Junction Devices .....	45
2.4.2.1	Efficiency in the p Region for the Electrons .....	45
2.4.2.2	Sample Calculation for p-Region Efficiency .....	46
2.4.2.3	Efficiency in the n Region for the Holes .....	46
2.4.3	Power Output of the Cell .....	50
2.4.4	Theoretical Conversion Efficiencies of Single-Junction Si and GaAs Solar Cells .....	54

2.4.4.1	Solar Module Power Conversion Efficiency as a Function of Open-Circuit Voltage, Short-Circuit Density, Sun Concentration Factor, and Form Factor (FF) .....	58
2.4.4.2	Maximum Output Power Density at 1 AMO and 300 K Temperature.....	60
2.4.5	Optimum Open-Circuit Voltage for Single-Junction Solar Cells .....	60
2.4.5.1	Open-Circuit Voltage for p-n Junction Devices in Diffusion Limited Cases.....	61
2.4.5.2	Open-Circuit Voltage as a Function of Sun Concentration Factor and Temperature.....	64
2.5	Overall Conversion Efficiency of Solar Cells .....	64
2.5.1	Junction Efficiency .....	65
2.5.2	Contact Efficiency .....	65
2.5.3	Absorption Efficiency .....	66
2.5.4	Reflection Efficiency.....	66
2.5.5	Overall Theoretical or Net Conversion Efficiencies of Si and GaAs Solar Cells.....	66
2.6	Critical Design and Performance Parameters for Silicon and Gallium Arsenide Solar Cells .....	66
2.7	Solar Cell Design Guidelines and Optimum Performance Requirements .....	67
2.8	Summary.....	68
	References.....	69

**3 Classification of Solar Cells Based on Performance, Design Complexity, and Manufacturing Costs.....**

3.1	Introduction .....	71
3.2	Identification of Design Aspects and Critical Design Parameters for Low-Cost, High-Efficiency Solar Cells .....	72
3.3	Description of Potential Low-Cost, High-Efficiency Cells.....	73
3.3.1	Low-Cost, High-Efficiency Passivated Emitter and Rear Cell (PERC) Devices.....	73
3.3.2	Mechanical Scribing Process for Fabrication of PERC Devices.....	74
3.3.3	Fabrication Steps .....	75
3.3.4	Performance Levels of PERC and MS-PERC Cells.....	76
3.4	Silicon Point-Contact Concentrator Solar Cells.....	76
3.4.1	Device Modeling Parameters.....	77
3.4.2	Carrier Density in Various Regions of the Device .....	79
3.4.3	Terminal Voltage.....	80

3.4.4	Photogeneration Profile of the Solar Cell.....	81
3.4.5	Techniques to Increase the Conversion and Quantum Efficiencies of the Cells.....	81
3.4.6	Critical Design Parameter Requirements for Higher Solar Cell Performance.....	82
3.4.7	Conclusions on SPCSC Solar Cells.....	84
3.5	V-Groove Multijunction (VGMJ) Solar Cells.....	84
3.5.1	Introduction.....	85
3.5.2	Description and Critical Elements of the VGMJ Solar Cell.....	86
3.5.3	Fabrication Procedure for VGMJ Cells.....	87
3.5.4	Performance Parameters of VGMJ Cells.....	88
3.5.4.1	Collection Efficiency of the VGMJ Solar Cell.....	88
3.5.4.2	Fundamental Collection Efficiency.....	90
3.5.4.3	Internal Collection Efficiency.....	91
3.5.4.4	Reflection Loss in the VGMJ Cell.....	93
3.5.4.5	Open-Circuit Voltage and Voltage Factor.....	93
3.5.4.6	Fill Factor (FF) of a Cell.....	94
3.5.4.7	Total Conversion Efficiency of a VGMJ Solar Cell.....	95
3.6	Potential Advantages of VGMJ Solar Cells.....	95
3.7	Multiple-Quantum-Well (MQW) GaAs Solar Cells.....	98
3.7.1	Introduction.....	98
3.7.2	Impact of Capture and Escape Times on Device Performance.....	99
3.7.3	Performance Parameters for the Baseline Bulk Al <sub>x</sub> Ga <sub>1-x</sub> /GaAs Solar Cells.....	99
3.7.4	Electric Field Profiles and Carrier Density Distribution in AlGaAs Devices.....	101
3.7.5	Impact of Physical Dimensions of the Quantum-Well on Solar Cell Performance.....	102
3.8	Summary.....	103
	References.....	104
<b>4</b>	<b>Techniques to Enhance Conversion Efficiencies of Solar Cells.....</b>	<b>105</b>
4.1	Introduction.....	105
4.2	Impact of Contact Performance and Design Parameters on Conversion Efficiency.....	106
4.3	Intensity Enhancement in “Textured Optical Sheets” (TOS) Used in Solar Cells.....	107

4.4	Nanoparticle Plasmons Best Suited for Solar Absorption Enhancement .....	110
4.4.1	Nanotechnology Concepts to Enhance Solar Cell Conversion Efficiency .....	110
4.5	Laser-Based Processing to Boost Conversion Efficiency and Reduce Production Costs for Solar Cells .....	111
4.5.1	Crystalline Silicon Solar Cells Most Likely to Get Most Benefits from the Deployment of Laser Technology .....	112
4.5.2	Fabrication Steps Using Laser Technology .....	112
4.5.2.1	Lasers Offer “Green” Technology .....	113
4.5.2.2	Laser-Based Technology Best Suited for Thinner Wafers .....	114
4.5.2.3	Edge Isolation Is the Most Critical Part of c-Si Production Lines .....	114
4.5.2.4	Laser Types and Performance Parametric Requirements .....	115
4.5.2.5	Impact of “Microcracks” on Solar Cell Reliability and Yield .....	116
4.6	Three-Dimensional Nanotechnology-Based Solar Cells .....	116
4.6.1	3-D Solar Cells Using an Array of Carbon Nanotubes (CNTs) .....	117
4.6.2	Solar Cell Design Configurations Using Nanowires, Nanocrystals, and Quantum Dots .....	117
4.6.3	Multijunction Amorphous Nanotechnology-Based Solar Cells .....	119
4.7	Solar Concentrators for Efficiency Enhancement .....	120
4.7.1	Impact of Base Thickness of the Solar Cell on Conversion Efficiency .....	121
4.7.2	Impact of Sunlight Concentration Ratio on Other Performance Parameters of the Solar Cell .....	122
4.7.3	Optimum Cell Thickness .....	123
4.8	Solar Cells with Specific Shapes and Unique Junction Configurations to Achieve Higher Performance .....	124
4.8.1	Benefits of Bifacial Solar Modules .....	124
4.8.2	Performance Enhancement from a V-Shaped Solar Cell .....	125
4.8.3	Tandem Junction Cell .....	126
4.8.3.1	Modeling of TJC Parameters .....	126
4.8.3.2	Design Considerations for Optimum Cell Performance .....	130
4.8.3.3	Projected Performance Parameters of TJC .....	131

4.9 Summary..... 132  
 References..... 133

**5 Solar Cells Deploying Exotic Materials and Advanced Design Configurations for Optimum Performance..... 135**

5.1 Introduction ..... 135

5.2 Potential Materials for Solar Cell Applications ..... 136

5.2.1 Critical Performance Parameters and Major Benefits of Materials..... 137

5.2.2 Critical Properties Requirements of Semiconductor Materials..... 137

5.2.2.1 Amorphous Silicon (a-Si) Material..... 139

5.2.3 Efficiency Limitations Due to Properties of Material and Deposition Techniques ..... 140

5.2.4 Impact of Deposition Process on Cell Efficiency and Yield ..... 140

5.2.5 Optoelectronic Properties of Nanocrystalline Silicon Materials..... 141

5.2.6 Impact of Various Interface Layers on the Performance Parameters of nc-Si:H-Based PIN Solar Cell ..... 142

5.2.6.1 Short-Current Density, Fill Factor (FF), Open-Circuit Voltage, and Conversion Efficiency of a PIN Solar Cell Using nc-Si:H.... 143

5.3 Performance Capabilities and Structural Details of Solar Cells Employing Exotic Materials ..... 144

5.3.1 Performance Capabilities and Structural Details ..... 144

5.3.1.1 Amorphous Silicon Solar Cell Devices ..... 145

5.3.1.2 Thin Films of Copper Indium Diselenide (CIS) and Copper Indium Diselenide Gallium (CIGS)..... 146

5.3.1.3 Benefits and Drawbacks of Ternary Compound Semiconductor Material Used in the Fabrication of CIS and CIGS Solar Cells.... 147

5.3.1.4 Cadmium Telluride (CdTe) Solar Cells ..... 148

5.3.1.5 Solar Cells Using Thin Films of CdHgTe ..... 150

5.3.2 MIS Solar Cells ..... 154

5.3.3 Schottky-Barrier Solar Cells ..... 155

5.3.3.1 Fabrication Procedure for the SBSC ..... 156

5.3.3.2 Characteristics of the SBSC Device ..... 156

5.3.3.3 Dye-Sensitized Solar Cells..... 158

5.4 Performance Capabilities of Solar Cells Employing Nanotechnology Concepts ..... 158

5.4.1 Nanowire-Nanocrystal Solar Cells ..... 159

5.4.2	Solar Cells Using Silicon Nanowires.....	159
5.4.3	Solar Cells Using Zinc Oxide Nanorods.....	160
5.5	Multijunction Solar Cells .....	160
5.5.1	Anatomy of a Multijunction Solar Cell.....	161
5.5.2	Space and Commercial Applications.....	162
5.5.3	Market for MJ Solar Devices .....	162
5.6	Solar Cells Using Polymer Organic Thin-Film Technology .....	162
5.6.1	Why Organic Thin-Film Solar Cells? .....	163
5.6.2	Anatomy of the Organic Thin-Film Solar Cell and Its Operating Principle .....	164
5.6.3	Polymer Semiconductor Solar Cells Incorporating CNT-Based Electrodes .....	165
5.6.3.1	Conversion Efficiency of Organic Solar Cells .....	165
5.6.3.2	Organic Solar Cells with Multilayer Configurations .....	166
5.7	Summary.....	167
	References.....	168
<b>6</b>	<b>Solar Cell and Array Designs Best Suited for Space Applications.....</b>	<b>171</b>
6.1	Introduction .....	171
6.2	Material Requirements for Solar Cells Used in Space .....	172
6.2.1	Why Silicon for Space-Based Solar Cells?.....	173
6.2.2	Cadmium Telluride (CdTe) Solar Cells .....	174
6.2.3	Justification for Use of Thin-Film Technology for Solar Cells .....	176
6.2.4	Performance Capabilities and Limitations of Potential Thin-Film Technologies.....	177
6.3	Performance Parameters for Solar Cells in Space.....	178
6.3.1	Conversion Efficiency of Silicon Solar Cells.....	179
6.3.2	Relative Solar Cell and Array Costs Using Silicon Technology.....	179
6.3.3	Weight of Solar Cells and Arrays Using Silicon Technology.....	180
6.3.4	Maximum Electrical Power Output from Silicon Solar Cells .....	181
6.3.5	Critical Performance Requirements for Solar Arrays for Space Applications.....	181
6.4	Impact of Space Radiation on Solar Cell Performance .....	184
6.4.1	Performance Degradation from Space Radiation to Solar Cells .....	184
6.4.2	Impact of Space Radiation on the Performance of Silicon Solar Cells.....	185

6.4.3	Impact of Space Radiation on the Performance of GaAs Solar Cells.....	187
6.5	Effects of Operating Temperature on Open-Circuit Voltage.....	188
6.5.1	Impact of Operating Temperature on Open-Circuit Voltage of Silicon Solar Cells.....	188
6.5.1.1	Low-Energy Proton Damage in Ion-Implanted and Diffused Silicon Solar Cells.....	189
6.5.2	Impact of Operating Temperature on the Performance of Heterojunction Gallium Arsenide (AlGaAs-GaAs) Solar Cells.....	189
6.5.3	Advanced High-Efficiency Silicon Solar Cells.....	191
6.5.4	High-Efficiency Triple-Layer Amorphous Solar Cell for Space Applications.....	191
6.5.5	Effects of Proton Energy and Nuclear Particle Radiation on the Performance of Silicon Solar Cells.....	192
6.6	Multijunction Solar Cells for Space Applications.....	193
6.6.1	Unique Design and Performance Parameters of Multijunction GaInP/GaAs/Ge Solar Cells.....	194
6.6.2	Impact of Temperature in Space on the Conversion Efficiencies of Multijunction GaInP/GaAs/Ge Solar Cells.....	195
6.6.3	Comparison of BOL and EOL Efficiencies of Various High-Efficiency Solar Cells.....	196
6.6.4	Impact of Space Radiation on the GaAs Subcell.....	197
6.7	Solar Array Design for Space Applications.....	199
6.7.1	Solar Array Design Requirements for Reliable Performance over a Specified Life Span.....	199
6.7.2	Solar Array Orientation Requirements.....	201
6.7.3	Electrical Power Output Capability of a Solar Array.....	201
6.7.4	Body-Mounted Solar Array Surface Temperatures.....	202
6.7.5	Mechanical Design Configurations for Space-Based Solar Arrays.....	204
6.7.5.1	Design Requirements for Intercell and Intermodule Connections.....	204
6.7.5.2	Sources of Weight Contributions to Solar Arrays.....	206
6.8	Summary.....	206
	References.....	207
<b>7</b>	<b>Design Requirements for Stand-Alone and Grid-Connected PV Systems.....</b>	<b>209</b>
7.1	Introduction.....	209

7.2	Grid-Connected PV Power Systems.....	210
7.2.1	General Description of a Grid-Connected PV System .....	211
7.2.2	Roof-Mounted Solar Panel Installation Scheme and System Cost Breakdown .....	211
7.3	Stand-Alone PV Power Systems.....	213
7.3.1	Design Configuration and Critical Performance Requirements for Stand-Alone PV Power Systems .....	213
7.3.1.1	Water Heater Design Using Solar Technology .....	213
7.3.1.2	Description of Critical Components of the Solar Hot Water System.....	214
7.3.1.3	Cost of Domestic Solar Water Heaters.....	215
7.3.1.4	Federal and State Tax Incentives for Solar System Installations .....	216
7.3.1.5	Estimation of Solar Collector Area Needed to Meet Hot Water Consumption Requirements.....	216
7.3.1.6	Design Requirements and Description of Solar Collectors .....	216
7.3.1.7	Cost Estimates for a Typical Hot Water System .....	219
7.3.2	Closed-Loop Active Hot Water System Using Solar Technology.....	221
7.3.2.1	Major Component Requirements for a Closed-Loop Hot Water System .....	222
7.4	Solar Heaters for Swimming Pools.....	223
7.4.1	Solar Panel Requirements for Pool Heating System .....	223
7.4.2	Operational Requirements of a Solar Swimming Pool Heater.....	224
7.5	Tower Top Focus Solar Energy Collector System.....	224
7.5.1	Operating Principle of the TTFSE Collector System .....	225
7.5.2	Heliostat System Configuration.....	226
7.5.2.1	Alternate Design Approach for a Heliostat System .....	227
7.5.3	Major Benefits of Tower Top Focus Collector Systems .....	227
7.5.4	Impact of Critical Element Parameters on System Performance .....	227
7.5.5	Impact of Environmental Effects on Mirror Surface.....	228
7.5.5.1	Performance Parameters of Critical Elements of the System .....	228
7.5.6	Preliminary Design Approach .....	229
7.5.6.1	Estimation of the Power Redirected by the Mirrors .....	229

7.5.6.2	Techniques to Achieve Optimum System and Mirror Performance.....	230
7.5.6.3	Performance Parameters for the Boiler and Solar Collector.....	230
7.5.7	Economic Feasibility of the Tower Top Focus Collector System .....	234
7.5.8	Impact of Solar Energy Levels on the Tower Focus Solar Energy Collector.....	237
7.6	Summary.....	237
	References.....	238

## **8 Performance Capabilities and Economic Benefits of Potential**

<b>Alternate Energy Sources .....</b>	<b>241</b>	
8.1	Introduction .....	241
8.2	Alternate Energy Sources and Their Installation Costs and Electrical Power Generating Capacities .....	242
8.3	Energy Sources Best Suited for Various Organizations .....	242
8.3.1	Geothermal Energy Source.....	244
8.3.2	Solar Power Installations .....	245
8.4	Hydroelectric Power Plants.....	246
8.4.1	Micro-Hydroelectric Power Plants.....	246
8.4.2	Benefits of a Microhydro-Turbine Generator .....	247
8.5	Steam Turbo-Alternator Power Plants .....	248
8.5.1	Anatomy of a Steam Turbo-Alternator Power-Generating Plant.....	248
8.5.2	Maintenance and Operating Costs for an STPG Power Plant.....	249
8.6	Nuclear Power Plants.....	249
8.6.1	Major Design Aspects and Critical Elements of a Nuclear Power Plant .....	249
8.6.2	Benefits and Drawbacks of the Nuclear Power-Generating Installation.....	250
8.6.3	Costs for Erecting the Plant and Electricity Generation.....	250
8.6.4	Reasons for Temporary Setback for Deploying Nuclear Power Plants .....	250
8.7	Tidal Wave Energy Sources .....	251
8.7.1	Operating Principal of Tidal Wave Energy Sources .....	251
8.7.2	Benefits and Drawbacks of Tidal Wave Energy Sources.....	252
8.8	Wind Energy Sources .....	252
8.8.1	Affordability and Environmental Benefits of Wind Turbines .....	252
8.8.2	Worldwide Deployment of Wind Turbine Technology .....	253

8.9	Use of Solar Cells to Generate Electricity .....	253
8.9.1	Estimation of Greenhouse Gas Contents in Various Energy Sources .....	253
8.9.2	Installation and Reliability Requirements for Photovoltaic Cells and Solar Panels .....	254
8.9.3	Reliability and Operating Life of Solar Cells and Panels .....	254
8.9.4	Performance Degradation in Solar Cells, Solar Panels, and Inverters.....	255
8.9.5	Utility-Scale Concentrating Solar Power Programs.....	256
8.9.5.1	Requirements for Critical Elements and Ideal Locations for CSP Projects.....	257
8.9.5.2	Solar Thermal Power Systems .....	257
8.10	Worldwide Photonic Markets and Installation Capacities.....	259
8.10.1	PV Market Growth in Various Countries.....	259
8.10.2	Growth of Solar Installation Capacity .....	260
8.11	Performance Capabilities and Cost Estimates for Solar Cells and Panels .....	261
8.11.1	Production Cost and Conversion Efficiency for Various Solar Cells .....	262
8.11.2	Solar Panel Cost Estimates and Design Aspects.....	264
8.11.3	Pay-Back Period for the System and Performance Degradation Rate for Cells .....	265
8.11.4	Critical Parameters for Solar Panels .....	266
8.11.5	Sample Calculation for SP-200 Solar Panel.....	266
8.11.6	Electrical Power Consumption Requirements for a Residential Solar System .....	267
8.11.7	Typical Performance and Procurement Specifications for Solar Cells and Panels for Residential and Commercial Applications .....	268
8.11.7.1	Performance and Procurement Specifications for Solar Cells and Panels Currently Available .....	268
8.12	Solar Panel Installation Options and Requirements.....	269
8.12.1	Sloped-Roof Installation Option .....	269
8.12.2	Geometrical Considerations for Solar Panel Installation on a Flat Roof.....	269
8.12.3	Impact of Shadowing on Solar Panel Performance.....	270
8.13	Summary.....	271
	References.....	272
	<b>Index .....</b>	<b>273</b>