

ANALYSIS OF THE SOLAR MARKETS FOR CRYSTALLINE AND THIN FILM SOLAR CELLS

Table of Contents

Chapter 1	Introduction	1-1
Chapter 2	Solar Cell Technology	2-1
2.1	Introduction	2.1
2.2	Generations of development	2-2
2.2.1	First Generation	2-2
2.2.2	Second Generation	2-2
2.2.3	Third Generation	2-3
2.3	History	2-12
2.4	Theory of Operation	2-13
2.4.1	Simple explanation	2-13
2.4.2	Photogeneration of charge carriers	2-14
2.4.3	Charge carrier separation	2-15
2.4.4	The p-n junction	2-15
2.4.5	Connection to an external load	2-16
2.4.6	Equivalent circuit of a solar cell	2-16
2.5	Solar cell efficiency factors	2-17
2.5.1	Maximum-power point	2-17
2.5.2	Energy conversion efficiency	2-17
2.5.3	Fill factor	2-18
2.5.4	Quantum efficiency	2-18
2.5.5	Comparison of energy conversion efficiencies	2-18
2.5.5.1	Peak watt (or Watt peak)	2-19
2.5.5.2	Solar cells and energy payback	2-21

2.6	Light-absorbing materials	2-21
2.6.1	Bulk	2-22
2.6.1.1	Silicon	2-22
2.6.2	Thin films	2-23
2.6.2.1	CdTe	2-23
2.6.2.2	CIGS	2-24
2.6.2.3	CIS	2-25
2.6.2.4	Gallium arsenide (GaAs) multijunction	2-25
2.6.2.5	Light absorbing dyes	2-26
2.6.2.6	Organic/polymer solar cells	2-29
2.6.2.7	Silicon Thin Films	2-31
2.6.3	Nanocrystalline solar cells	2-34
2.7	Concentrating photovoltaics (CPV)	2-35
2.7.1	Introduction	2-35
2.7.2	Commercial reflectors	2-38
2.8	Overview of research on materials and devices	2-41
2.8.1	Silicon processing	2-42
2.8.2	Thin-film processing	2-46
2.8.3	Polymer processing	2-46
2.8.4	Nanoparticle processing	2-47
2.8.5	Transparent conductors	2-48
2.8.6	Perovskite Solar Cells	2-50
2.8.7	PERC (Passivated Emitter And Rear Cell)	2-51
Chapter 3	Solar Cell Manufacturing	3-1
3.1	Introduction	3-1
3.2	How Solar Cells Are Made	3-1

3.2.1	Silicon Solar Cell	3-6
3.2.2	Etching And Texturing	3-10
3.2.3	Diffusion And Edge Isolation	3-10
3.2.4	Anti-Reflection Coating	3-11
3.2.5	Metallization	3-11
Chapter 4	Thin Film Technology	4-1
4.1	Introduction	4-1
4.2	Silicon Deposition Technologies	4-3
4.2.1	Amorphous Silicon Deposition	4-3
4.2.2	Microcrystalline Silicon Deposition	4-5
4.3	Compound Semiconductor Deposition Technologies	4-9
4.3.1	Introduction	4-9
4.3.2	CdTe – Cadmium Telluride	4-17
4.3.3	CIGS - Copper Indium Gallium Selenide	4-24
4.3.4	GaAs – Gallium Arsenide	4-32
4.3.5	Perovskite	4-35
Chapter 5	Solar Markets	5-1
5.1	Introduction	5-1
5.2	Key Growth Drivers	5-3
5.2.1	Government Incentives	5-3
5.2.2	Low Cost Solar	5-5
5.2.3	Large Market Among Underserved Populations	5-5
5.3	Challenges Facing The Solar Power Industry	5-6
5.4	Cost Of A Photovoltaic System	5-7

5.5	Operating Metrics Of A Photovoltaic System	5-9
5.6	Types Of PV System	5-10
5.6.1	Grid Connected Sector	5-10
5.6.2	Off-Grid Sector	5-11
5.6.3	Market Development	5-12
5.7	Market Analysis	5-14
5.7.1	Solar Cell Market	5-14
5.7.2	Polysilicon Solar Cell Market	5-47
5.7.2.1	Wire Saw Wafering Technology	5-59
5.7.2.2	Kerfless Wafering	5-62
5.7.3	Thin Film Solar Cell Market	5-69
5.7.3.1	Driving Forces	5-69
5.7.3.2	Competing Technologies	5-75
5.7.3.3	Third-Generation Technologies	5-80
5.7.4	Thin Film Solar Cell Equipment Market	5-86
5.7.5	Substrates	5-86
5.7.6	Manufacturing Costs	5-90
5.8	Disruptive Technologies	5-96
List of Figures		
2.1	Light Absorption Through Layers In A Multijunction Cell	2-5
2.2	Triple Junction a-Si/a-SiGe/a-SiGe Cell Structure	2-6
2.3	A Two-Junction Amorphous-Silicon Solar Cell	2-7
2.4	Solar Cell Technology Roadmap	2-9
2.5	Best Research-Cell Efficiencies	2-20
2.6	Dye Sensitized Solar Cell Schematic	2-28
2.7	Bulk Heterojunction Solar Cell	2-30
2.8	Schematic Of Sliver Cell	2-44

3.1	Diagram Of Solar Cell	3-2
3.2	Cross Section Of A Solar Cell Under Illumination	3-3
3.3	Conventional vs PERC Processing	3-5
3.4	Polysilicon Manufacturing And Supply Chain	3-9
4.1	Sharp's Triple-Junction Solar Cell	4-6
4.2	Factory Flow For 20 MW/Year CGS Facility	4-4
4.3	Schematic Of CdTe And CIGS Device Structures	4-14
4.4	CdTe Thin Film Deposition By VTD	4-20
4.5	CdTe Thin Film Deposition By Close Space Sublimation (CSS) Schematic	4-21
4.6	CdTe Thin Film Deposition By VTD2	4-23
4.7	CIGS Deposition System By Evaporation	4-26
4.8	Cross-Sectional Schematic Diagram Of The InGaP/InGaAs/Ge ATJ Cell	4-34
4.9	Cross-Sectional Schematic Diagram Of a Perovskite Cell	4-36
5.1	Cost Projections of Solar Panels	5-8
5.2	Evolution Of Global Annual Installations	5-15
5.3	Solar Vendor Market Shares – 2000	5-19
5.4	Solar Vendor Market Shares – 2001	5-20
5.5	Solar Vendor Market Shares – 2002	5-21
5.6	Solar Vendor Market Shares – 2003	5-22
5.7	Solar Vendor Market Shares – 2004	5-23
5.8	Solar Vendor Market Shares – 2005	5-24
5.9	Solar Vendor Market Shares – 2006	5-25
5.10	Solar Vendor Market Shares – 2007	5-26
5.11	Solar Vendor Market Shares – 2008	5-27
5.12	Solar Vendor Market Shares – 2009	5-28
5.13	Solar Vendor Market Shares – 2010	5-29
5.14	Solar Vendor Market Shares – 2011	5-30
5.15	Solar Vendor Market Shares – 2012	5-31
5.16	Solar Vendor Market Shares – 2013	5-32
5.17	Solar Vendor Market Shares – 2014	5-33
5.18	Solar Vendor Market Shares – 2015	5-34

5.19	Solar Vendor Market Shares – 2016	5-35
5.20	Solar Cell Production by Region – 2016	5-37
5.21	Solar Cell Forecast - 2010-2020	5-38
5.22	Solar Cell Production By Type	5-39
5.23	Thin Film Solar Cell Production By Type – 2010-2020	5-41
5.24	Polysilicon Production And Consumption (MT)	5-51
5.25	Polysilicon Sales by Region	5-52
5.26	China Polysilicon Imports	5-54
5.27	Kerfless Wafering	5-67
5.28	Best Research-Cell Efficiencies	5-76
5.29	Schematic Diagrams Of Thin-Film CdTe, CIGS, and a-Si Thin Film PV Devices	5-77
5-30	Thin Film Solar Cell Power As A Percentage Of Total Solar Power - 2005-2020	5-84
5-31	Thin Film Solar Cell Power As A Percentage Of Total Solar Power - 2003-2020	5-85
5.32	Schematic Thin-Film Roll-To-Roll Equipment	5-66
List of Tables		
3.1	Polysilicon Capacity Forecast	3-7
4.1	Thin Film CIGS Solar Cells Efficiencies	4-11
4.2	Highest Efficiencies PV Modules	4-13
5.1	Top 10 Solar Manufacturers By Shipments - 2015-2016	5-18
5.3	Market Share Of Solar Cells By Technology – 2008-2020	5-40
5.4	Polysilicon Production Capacities By Company – 2010-2017	5-48
5.5	Polysilicon Supply/Demand Forecast – 2013-2020	5-50
5.6	Wafering Technology Forecast	5-62
5.7	Wire Saw Companies	5-63
5.8	Saw Wire and Diamond Wire Companies	5-64
5.9	CdTe Thin Film Solar Cell Producers	5-71

5.10	CIGS Thin Film Solar Cell Producers	5-72
5.11	3G Thin Film Solar Cell Producers	5-74
5.12	CIGS Manufacturers and Deposition Methods	5-88
5.13	Cost Comparison Of Thin Film Technologies	5-91
5.14	Number Of Solar Equipment And Materials Companies – Chinese, U.S. Other	5-93
5.15	Top Non-Chinese Equipment Supplier Revenues	5-95