National Renewable Energy Laboratory
Innovation for Our Energy Future

National R&D Thin Film Photovoltaic Teams: A Success Story

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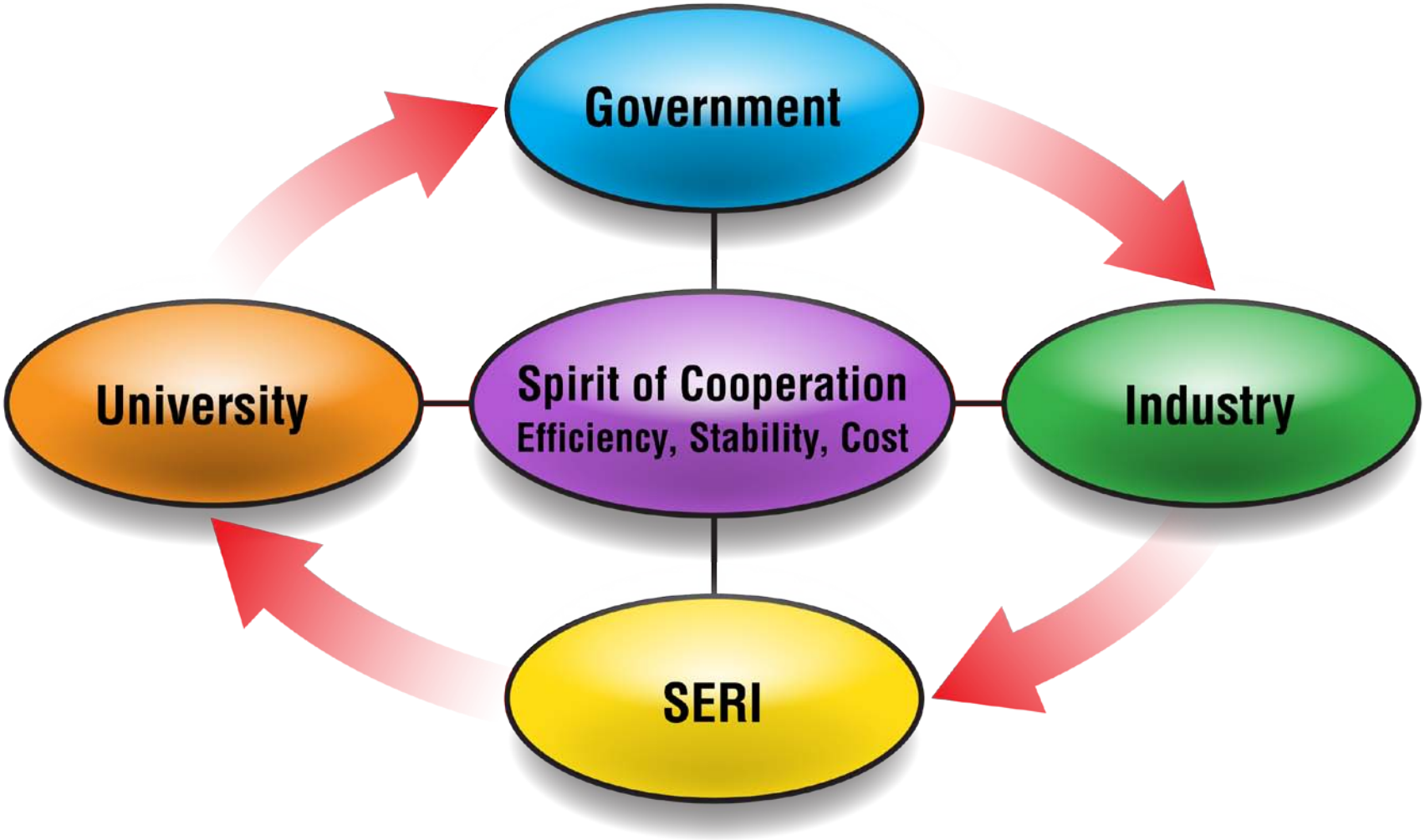
Bolko von Roedern, Ph.D.

NSF PV Workshop
Colorado School of Mines
Golden, Colorado

May 6-7, 2010

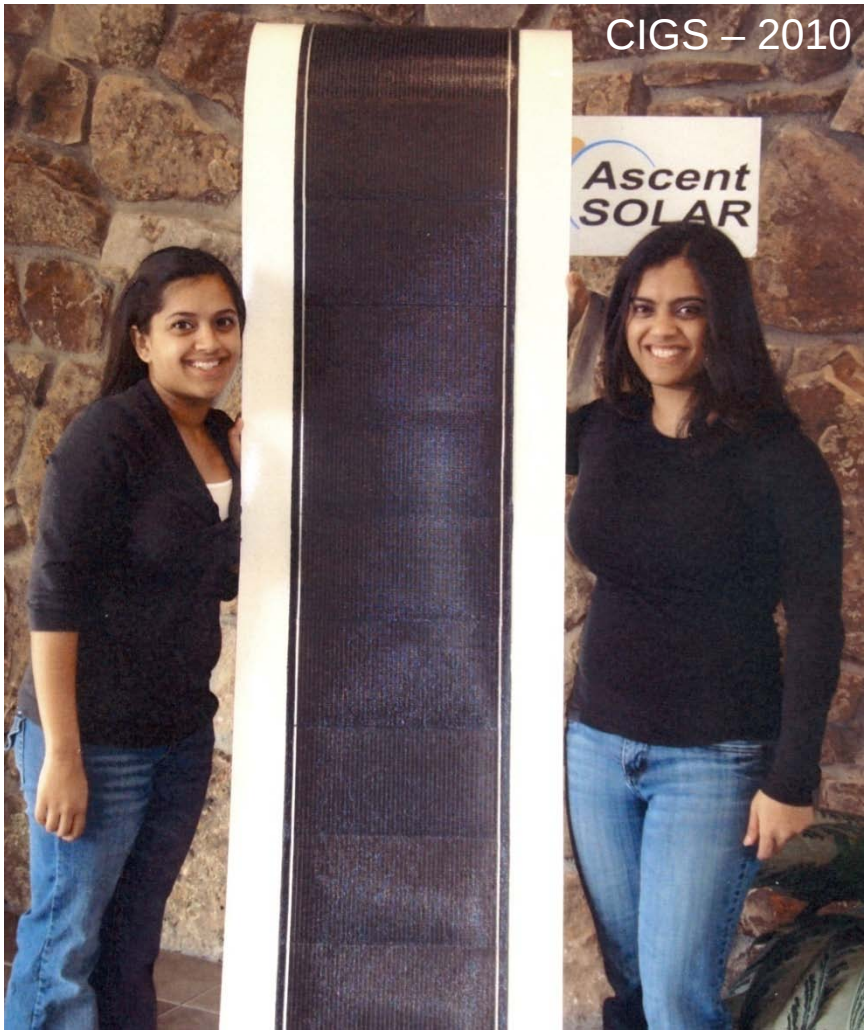
NCPV
National Center for Photovoltaics

Model


Government
University
Spirit of Cooperation
Efficiency, Stability, Cost
Industry
SERI

Thin Film CIGS – Prototype Modules

ARCO Solar



Purpose

- Support the successful introduction of U.S. thin-film products by addressing key near-term technical issues at U.S. business concerns committed to thin-film PV commercialization.
- Support advanced (mid- and long-term) thin-film R&D needed by industry for future product competitiveness including improving module performance, cost of kilowatt-hour produced, and reliability of thin-film PV technologies.

Thin Film PV Partnership Program

"Ground Rules"

- All subcontract awardees must participate
- Others may participate
- No sideline participants
- Active collaboration and exchange required
- Information shared during team activities should be non-proprietary
- Where voting is needed, funded industry partners vote counts three (3) times
- Team Members will decide:
  - Research topics
  - Strategies
  - Logistics and implementation
  - Team leaders

National Thin Film R&D Teams

- National a-Si R&D Team
- National CdTe R&D Team
- National CIS R&D Team
- National ES&H R&D Team

National a-Si/Thin Film-Si Team Meetings

- Louisville, KY; May 9-10, 1993
- Denver, CO; Oct. 15-16, 1993
- Lakewood, CO; May 24-25, 1994
- Lakewood, CO; Jan. 17-18, 1995
- Lakewood, CO; May 15-16, 1995
- Lakewood, CO; Jan. 12, 1996
- Breckenridge, CO; Aug. 24-26, 1996
- Newark, DE; April 30, 1997
- Golden (NREL), Jan. 23, 1998 (1st in Visitor's Center)
- Cooper Mountain, CO; Aug. 21, 1998
- San Francisco, CA; April 10, 1999
- Golden (NREL), Jan. 10-11, 2000
- Golden (CSM), Aug. 3-4, 2000
- Golden (CSM), May 31-June 1, 2001
- Golden (NREL), Feb. 25-26, 2002 (First Thin Film-Si Session)
- Golden (NREL), Jan. 9-10, 2003
- Vail, CO; Aug. 8-9, 2003
- San Francisco, CA; April 17, 2004
- Golden (NREL), May 19-20, 2005
- San Francisco, CA; April 17, 2006

National CdTe R&D Team Meetings

- December 5-9, 1994; Kona, HI
- May 16, 1995; Lakewood, CO
- January 22, 1996; Newark, DE
- May 15, 1996; Washington, DC
- Nov. 18, 1996; Lakewood, CO
- April 30, 1997; Newark, DE
- October 1, 1997; Anaheim, CA
- January 15-16, 1998; Cocoa, FL
- September 8, 1998; Denver, CO
- May 6-7, 1999; Golden, CO
- January 27-28, 2000; Golden, CO
- January 25-26, 2001; Golden, CO
- October 14, 2001; Lakewood, CO
- March 14-15, 2002; Cocoa, FL
- Oct. 31-Nov. 1, 2002; Golden, CO
- July 10-11, 2003; Golden, CO
- Feb. 26-27, 2004; Perrysburg, OH
- May 5-6, 2005; Golden, CO
- March 9-10, 2006; Golden, CO

National CIS R&D Team Meetings

- December 5-9, 1994; Kona, HI
- February 10-11, 1995; Golden, CO
- May 19-20, 1995; Lakewood, CO
- January 25-26, 1996; Newark, DE
- May 13, 1996; Washington, DC
- Nov. 22-23, 1996, Lakewood, CO
- May 2-3, 1997; Newark, DE
- September 29, 1997; Anaheim, CA
- April 16-17, 1998; Golden, CO
- September 11, 1998; Denver, CO
- February 25-26, 1998; Tampa, FL
- October 11-12, 1999, Golden, CO
- April 19-20, 2000; Denver, CO
- April 20-21, 2001; San Francisco, CA
- October 17, 2001; Lakewood, CO
- May 19, 2002; New Orleans, LA
- January 30-31, 2003, Golden, CO
- November 13-14, 2003; Cocoa, FL
- March 8-9, 2005; Golden, CO
- April 6-7, 2006; Golden, CO

National CdTe R&D Team Meeting

NREL Visitors Center • Golden, Colorado • March 9-10, 2006

Thursday, May 5

8:00 a.m. Breakfast
8:30 a.m. Opening Remarks Ullal/Meyers
8:45 a.m. Industry Update (First Solar /AVA Tech)
9:30 a.m. Device Physics Karpov/Sites
10:30 a.m.Break
10:45 a.m.Device Physics Continued
12:15 p.m.Stability Albin/Asher
1:15 p.m. Break
3:00 p.m. Materials Chemistry McCandless/Ohno
5:30 p.m. End of First Day

Friday, May 6

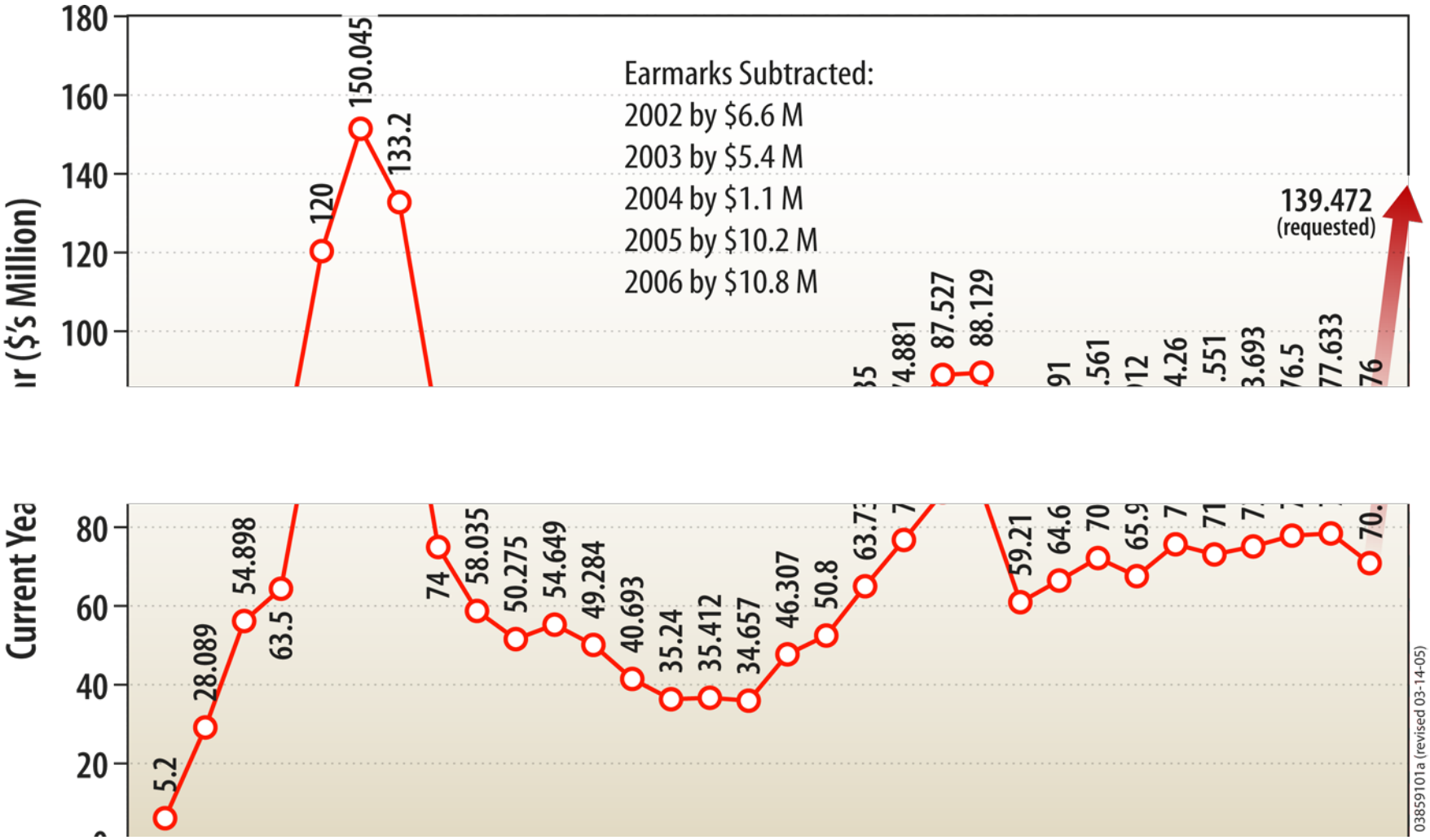
8:00 a.m. Breakfast
8:30 a.m. Mini-Workshop..ImprovingVoc Seymour
10:30 a.m.Break
10:45 a.m.Future Plans & Discussion Ferekides/Ullal
12:15 p.m.Lunch
1:15 p.m. Future Plans & Discussion Continued
2:30 p.m. End of Second Day

DOE/NREL Budget

Year	DOE EERE ($B)	DOE PV ($M)	NREL PV ($M)	NREL ($M)
1995	$ 1.2	$ 85	$ 48	$ 237
1996	0.8	60	39	175
1997	0.8	56	39.7	149
1998	0.9	62	44	173
1999	1.0	72	51?	176
2000	1.06	66	48	187
2001	1.2	75	58	215
2002	1.3	66	52	215
2003	1.3	66	55	230
2004	1.3	75	57	211
2005	1.3	77	51	202
2006	1.2	71	49	189

DOE PV Program Budget History

(Fiscal Year)



National CdTe R&D Team Members

Thin Film PV Partnership • Distribution List

Team Member	Organization	Phone #	Fax #	E-mail
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Alan Fahrenbruch	CSU	(650) 723-2591	(650) 725-4034	alanf@stanford.edu
Chris Ferekides	USF	(813) 974-4818	(813) 974-5250	ferekide@eng.usf.edu

CdTe Members List

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vkarpov@physics.utoledo.edu
ndalacu@canrom.com

National CdTe R&D Team Meeting

List of Attendees • March 9-10, 2006

No	Name	Organization
1.	Harin Ullal	NREL
2.	Jim Sites	CSU
3.	Xuanzhi Wu	NREL
4.	Bolko von Roedern	NREL
5.	Markus Gloeckler	FSLLC
6.	W.S. Sampath	CSU
7.	Al Enzenroth	CSU
8.	Caroline Corwine	CSU
9.	Rick Luess	CSU
10.	Alan Davies	CSU
11.	Tim Nagle	CSU
12.	Jun Pan	CSU
13.	Ana Kanevce	CSU
14.	Mowafak Al-Jassim	NREL

No	Name	Organization
15.	Kannan Ramanathan	NREL
16.	Dave Albin	NREL
17.	Samuel Demtsu	CSU
18.	Ramesh Dhere	NREL
19.	Roger Green	FSLLC
20.	Alan Fahrenbruch	ALF
21.	Tom McMahon	NREL
22.	Joe Beach	CSM
23.	Peter Meyers	FSLLC
24.	Ken Zweibel	NREL
25.	Brian McCandless	IEC
26.	Sally Asher	NREL
27.	Rommel Noufi	NREL
28.	Larry Olsen	PNNL

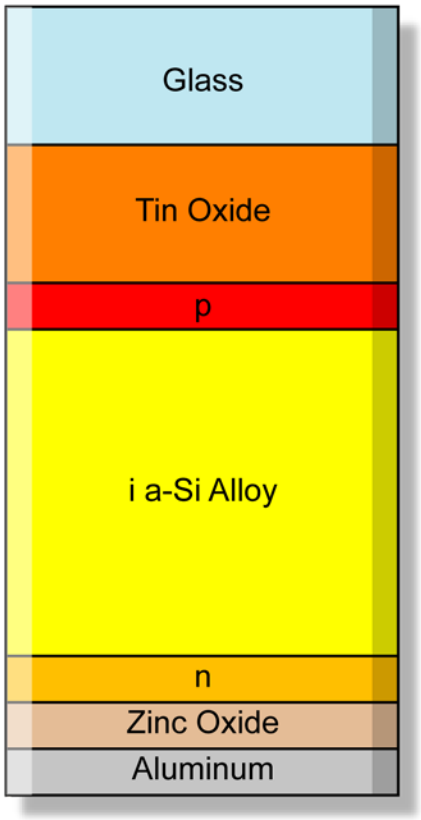
National R&D Team Members: Participants

- Academia
- Thin Film PV Industry
- NREL
- AFRL, BNL, NASA, NIST, Sandia

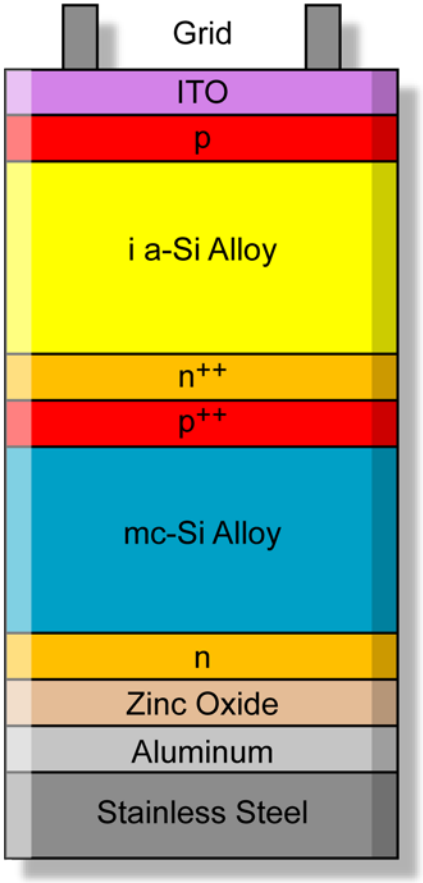
National a-Si R&D Team: Subteams

- Wide Bandgap – ~1.8 eV (Ge = 0%)
- Mid Bandgap – ~1.6 eV (Ge = 10%)
- Narrow Bandgap – ~1.4 eV (Ge = 40%)
- Devices – TCOs, Modeling, Scribing

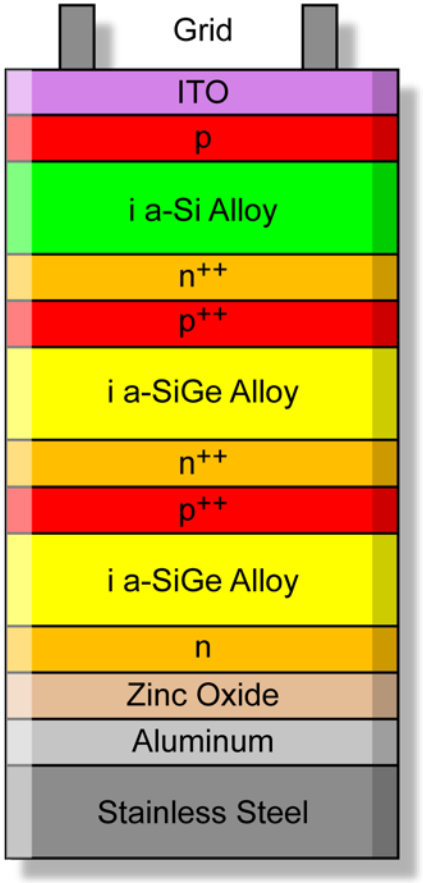
a-Si Solar Cell Structures



Single – Junction



Dual Gap
Double – Junction



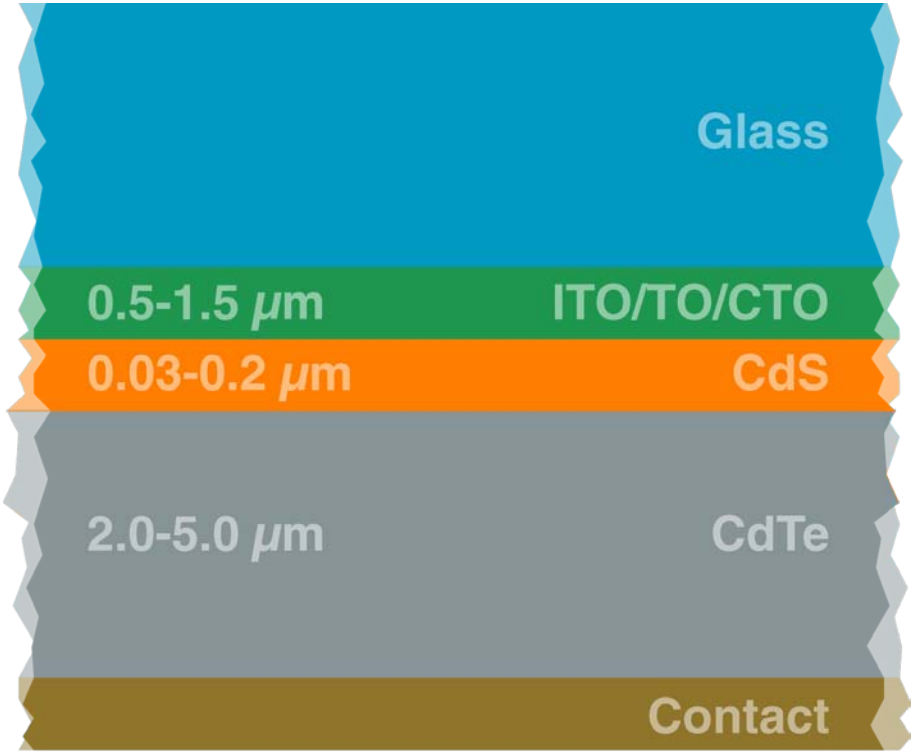
Triple – Junction

National CdTe R&D Teams: Subteams

- Device Physics
- Stability
- Materials Chemistry
- Mini-Workshop – Improving V_{OC}

Thin Film CdTe Solar Cells

CdTe



$\eta = 16.5\%$

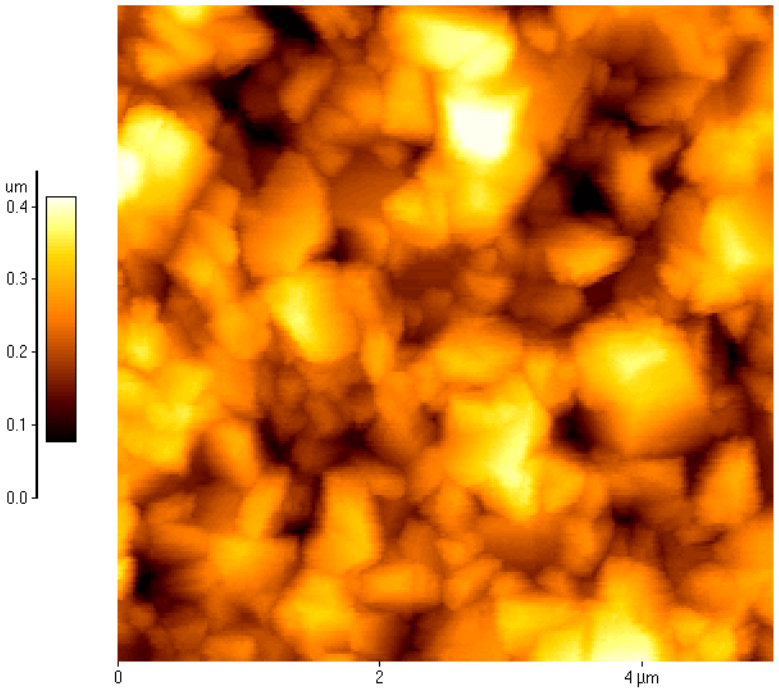
Thin Film CdTe Solar Cell Back Contacts

Metals	Others	
– Cu	– Graphite	– Sb_2Te_3/Metal
– Au	– Graphite (Cu, HgTe, Ni_2P)	– ZnTe: Cu/Metal
– Cu/Au	– As_2Te_3/Metal	– ZnTe: N/Metal
– Ni	– Cu_2Te/Metal	
– Ni/Al	– Ni_2P/Metal	
– Sb/Al	– $NiTe_2$/Metal	
– Sb/Au	– Te/As_2Te_3/Metal	

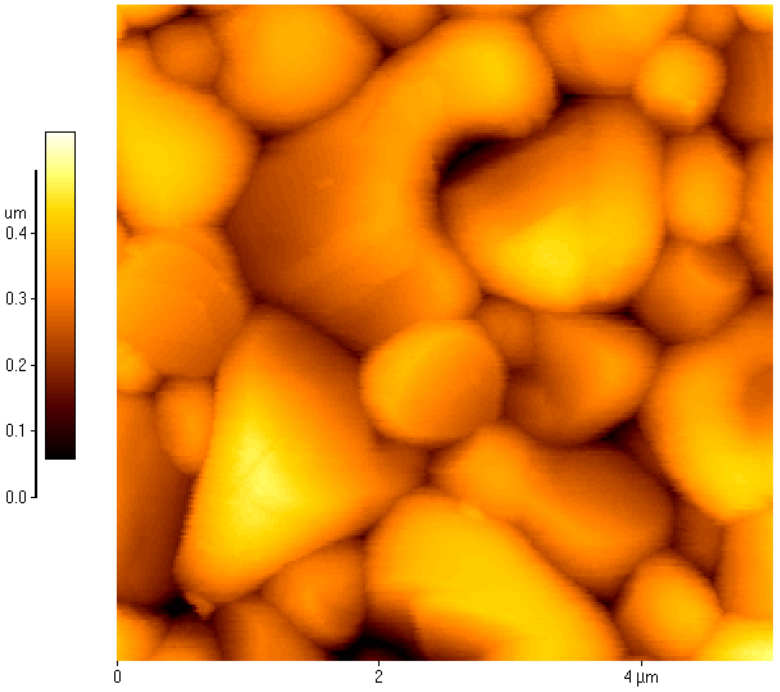
CdTe – Accelerated Life Testing

Illumination	0.5 Sun, 1 Sun, 2 Suns, Dark
Temperature	60, 70, 80, 90, 100, 110, 120°C
Ambient	Air, Ar, He, N_2, O_2
Bias	I_{SC}, V_{OC}, P_{MAX}, R_{rev}, F_{for}
Time	1 to 4000 hours
Etching	BM, BDH, NP, no etch
Measurements	I-V, Q-E, C-V, PL
Characterizations	AES, AFM, EDS, SEM, SIMS, XPS, XRD

$CdCl_2$ Heat Treatment



Before



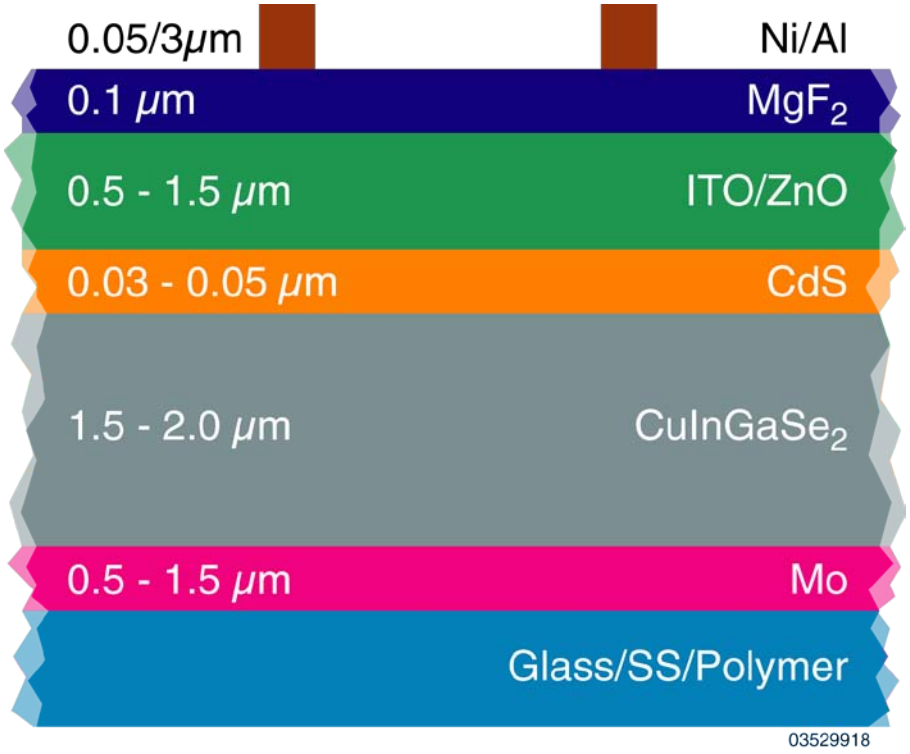
After

National CIS R&D Team: Subteams

- Junction
- Absorber Layers
- Contacts

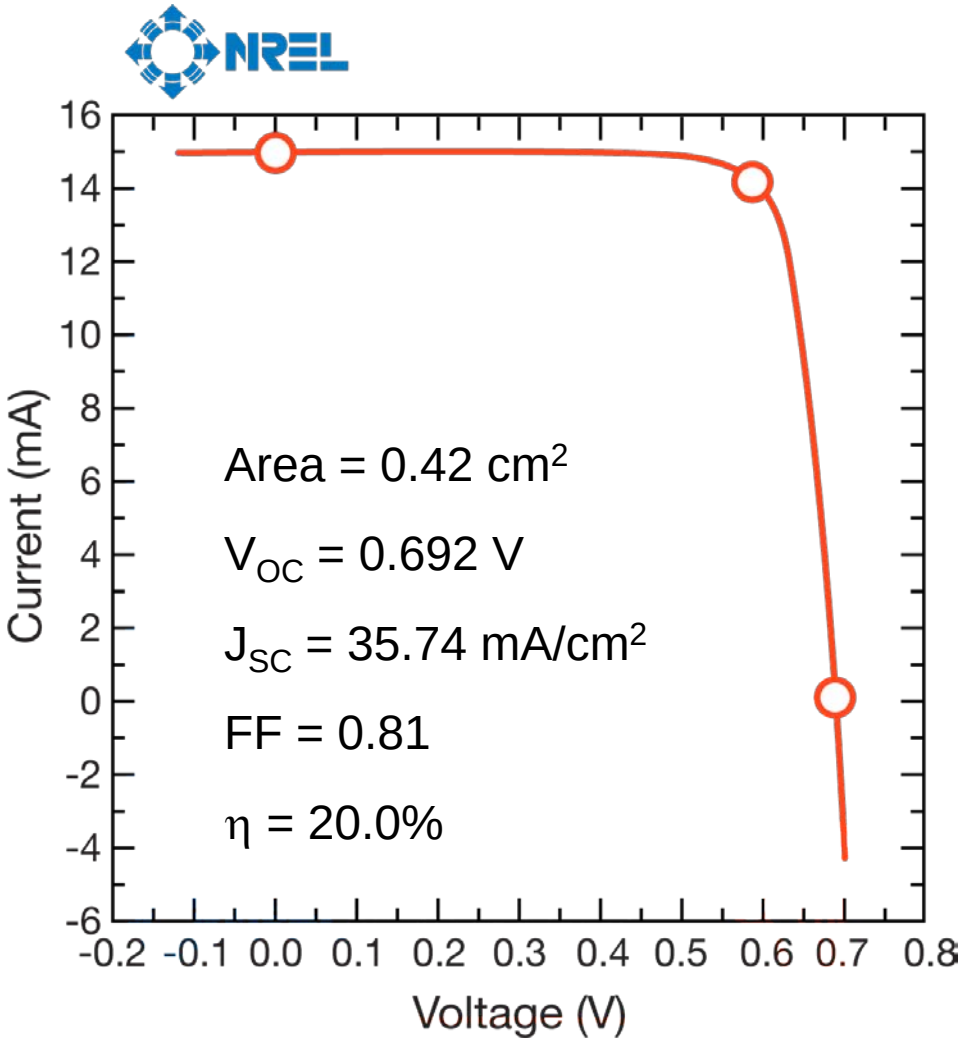
Thin Film CIGS Solar Cell

CIGS



$\eta = 20.0\%$

20.0% Thin Film CIGS Solar Cell



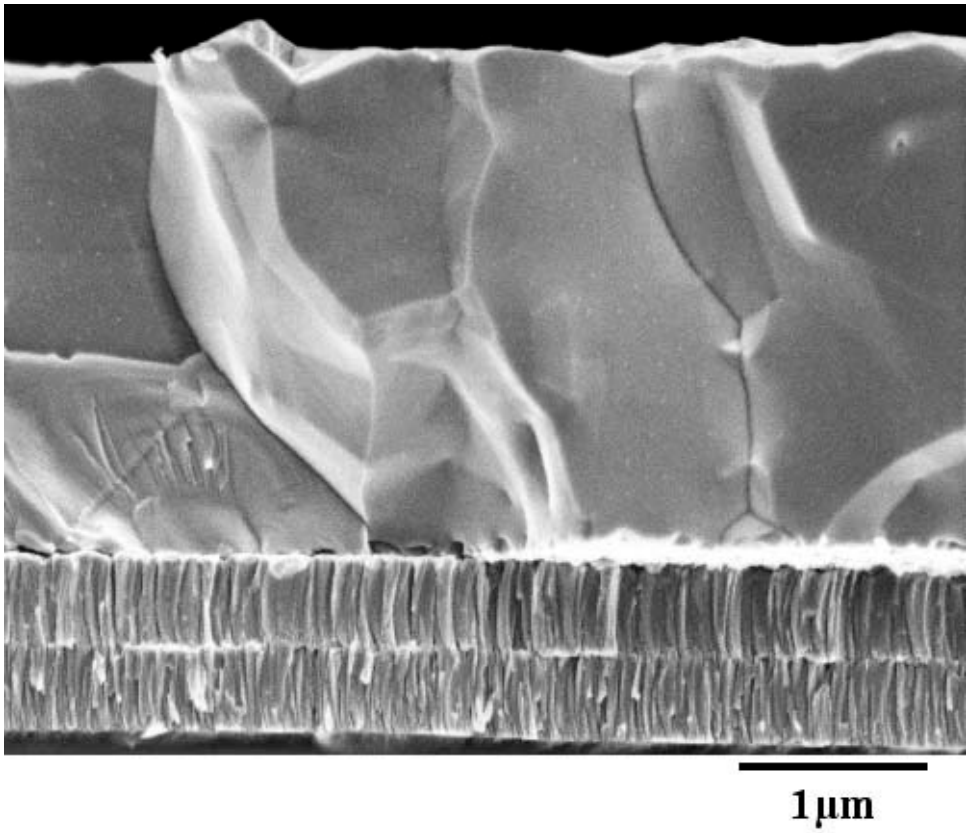
Heterojunction Partners – Buffer Layers

Material	Process
• Ga_2S_3	PVD
• Ga_2Se_3	PVD
• $(InGa)_2Se_3$	PVD
• $In(OH)_3$	CBD
• In_xS_y	CBD
• In_2Se_3	CBD
• SnO_2	CBD
• $Sn(S,O)_2$	CBD

Material	Process
• SrF_2	PVD
• $ZnIn_xSe_y$	PVD
• Zn_xMg_yO	Sputter
• ZnO	ALD, MOCVD
• $Zn(O,S,OH)_x$	CBD
• ZnS	CBD, PVD
• ZnSe	Sputter
• ZrO_2	CBD

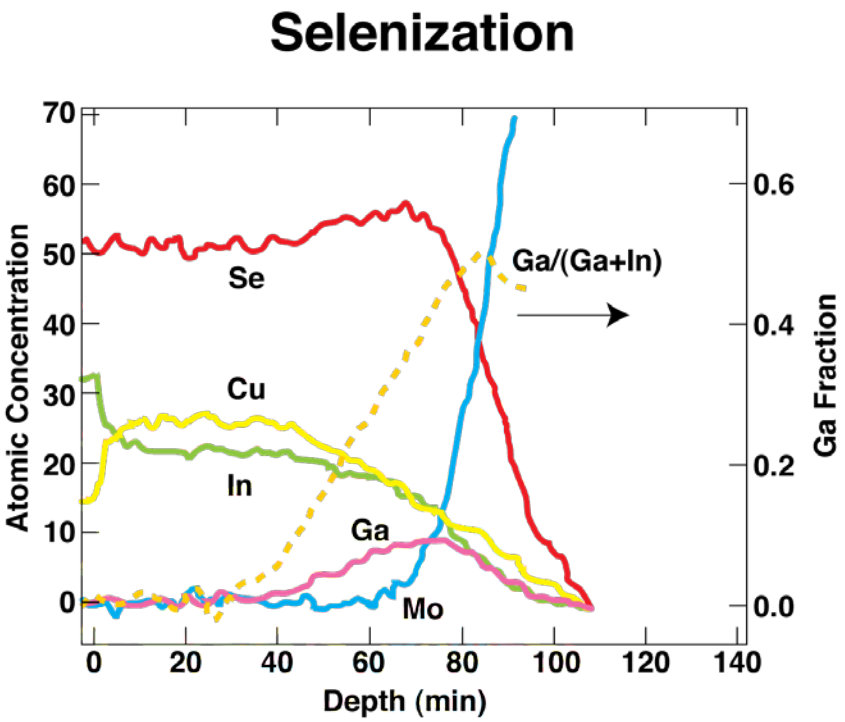
ALD - atomic layer deposition; **CBD** - chemical bath deposition; **PVD** - physical vapor deposition

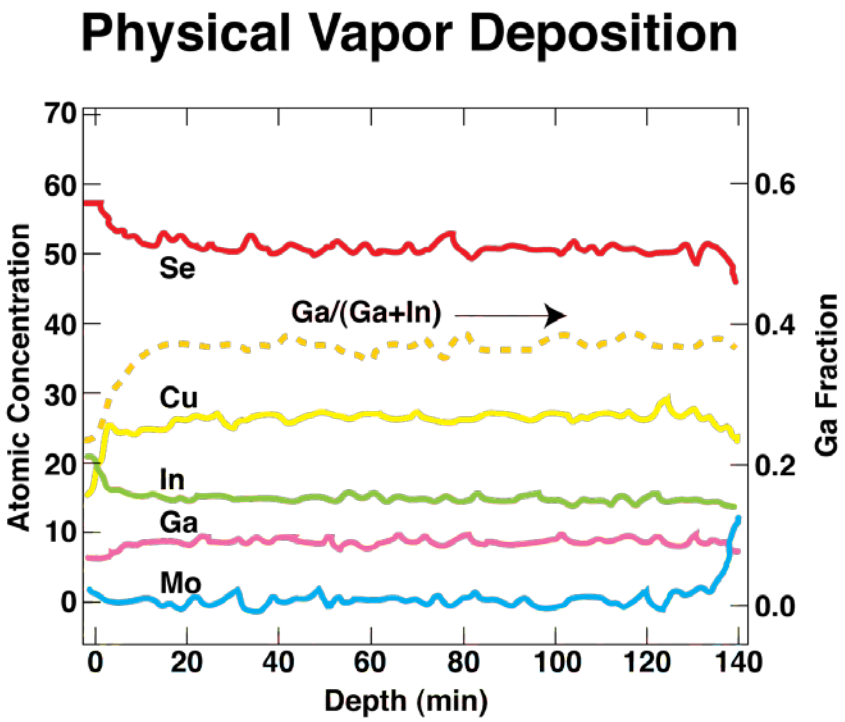
CIGS-SEM



η=19.3%, Ga/(Ga+In) 26%, E_g=1.13 eV

Thin Film CIGS Absorbers

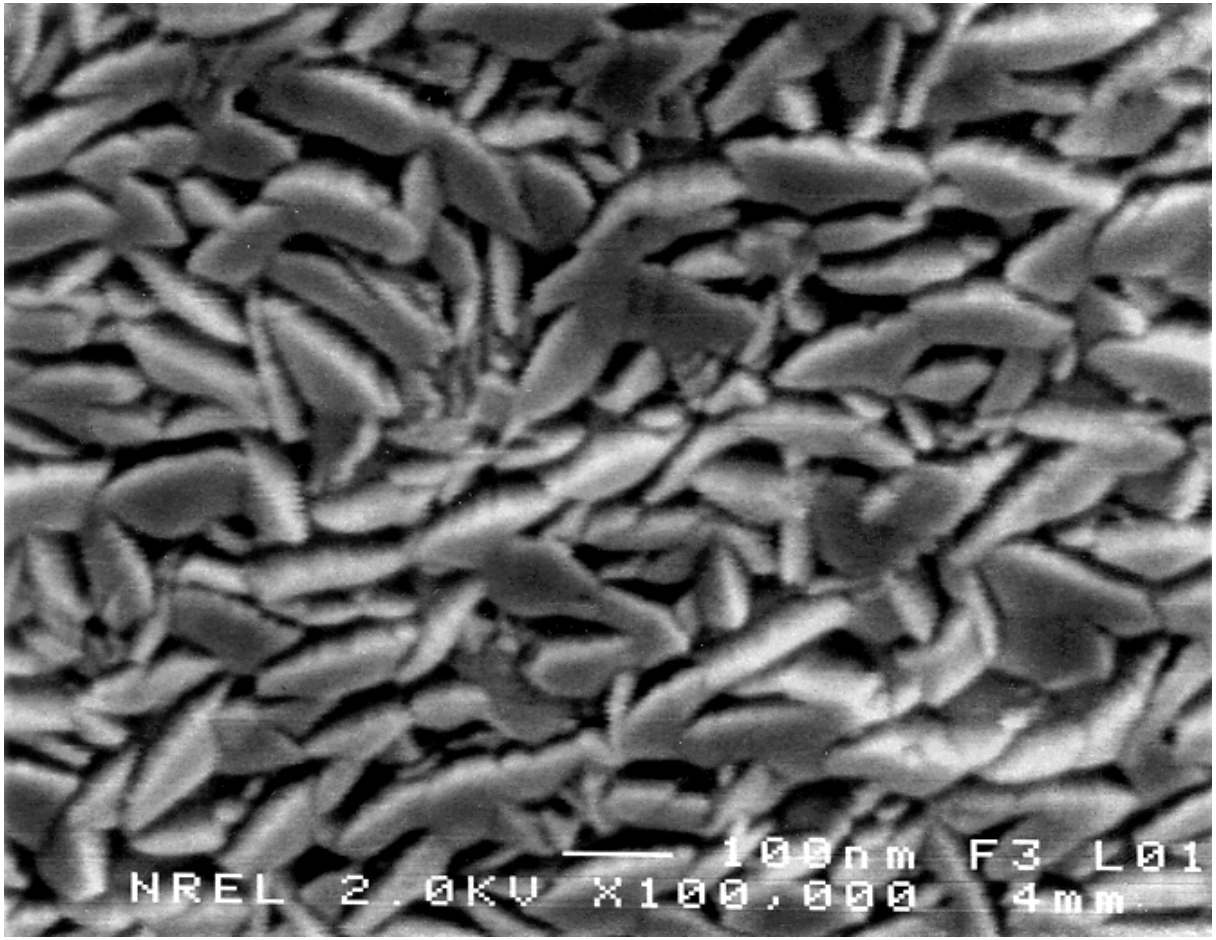




Thin Film CIGS Technology

Company	Substrate	Back Contact	Process	Front Contact
Shell Solar	Glass	Mo	Sputter/Selenization	ZnO
Global Solar	Steel	Mo	Coevaporation	ITO
Miasole	Steel	Mo	Sputter	ZnO
Würth Solar	Glass	Mo	Coevaporation	ZnO
Avancis	Glass	Mo	Sputter / RTP	ZnO
Daystar Tech	Glass	Mo	Sputter	ZnO
EPV	Glass	Mo	Sputter/Evaporation	ZnO
Ascent Solar	Polymer	Mo	Coevaporation	ITO
ISET	Glass/Flex	Mo	Ink/Selenization	ZnO
Nanosolar	Flexible	Mo	Print/RTP	ZnO
Heliovolt	Glass/Flex	Mo	FASST	ZnO
SoloPower	Steel	Mo	ED/RTP	ITO
Solyandra	Glass/Cyl.	Mo	Coevaporation	ZnO

SEM – Mo Back Contact



Outcome

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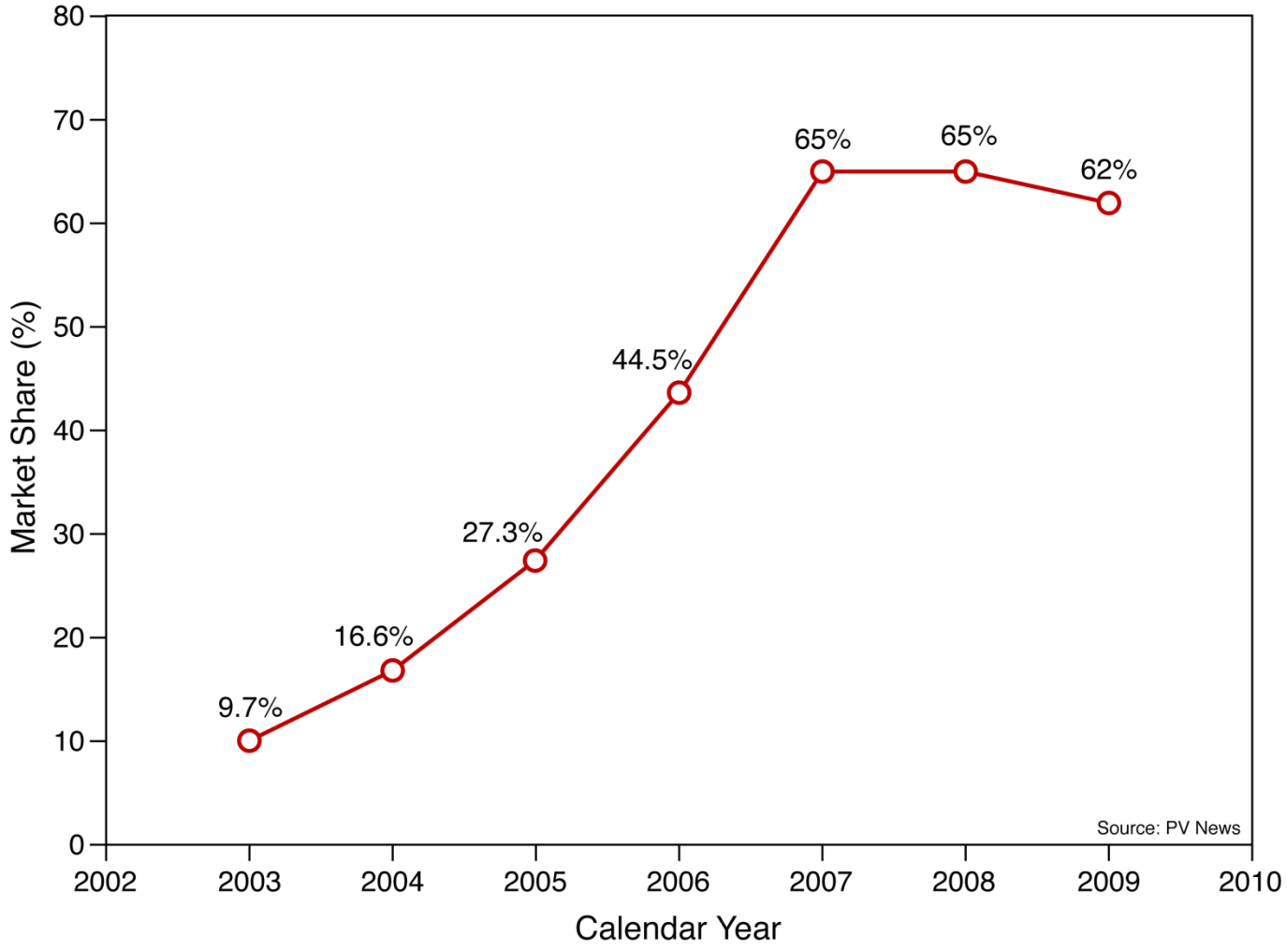
Success Story

Thin Film PV Market Share – USA



Thin Film PV Companies – USA

a-Si

Uni-Solar – MI
Applied Materials – CA
Power Films – IA
EPV Solar – NJ
MV Systems – CO
EPOD Solar – CA
Signet Solar – CA
Nano PV – NJ
Xunlight – OH
ProtoFlex – CO
New Solar Ventures – NM
Solar Thin Films – NJ
Sencera Int. – NC
Heliantlios – ID
Solasta – MA
Lightwave Power – MA

Thin-Si

Nanogram – CA
Solexel – CA
Crystal Solar – CA
Parachete Energy – SC
Ampulse – CO
AstroWatt – TX
SiGen – CA
Sierra Solar – CA

CdTe

First Solar – OH
Primestar Solar – CO
Abound Solar – CO
Calyxo – OH
Canrom – NY
Ascentool – CA
Nuvo Solar Energy – CO
Zia Watt Solar – TX
Solexant – CA
Sunovia Energy – FL
W&K Solar – OH
Bloo Solar – CA
EPIR Tech – IL
Xunlight 26 – OH
Van Guard – MA
SunPrint – CA
Reel Solar – CA
Wakonda Tech – MA

CIS

Global Solar – AZ
Miasole – CA
EPV Solar – NJ
Ascent Solar – CO
ISET – CA
Daystar – NY
Nanosolar – CA
Heliovolt – TX
Solo Power – CA
Solyndra – CA
RESI – NJ
Light Solar – NV
IBM – NY
JNL Solar – CA
Telio Solar – CA
AQT – CA
Nuvo Sun – CA
Optony – CA
Stion – CA
XSunX – OR
Sun King Solar – CA
Amelio Solar – NJ
Rennergy – NJ

Roll-to-Roll Triple-Junction Solar Cell

Deposition Plant of 30 MW Annual Capacity

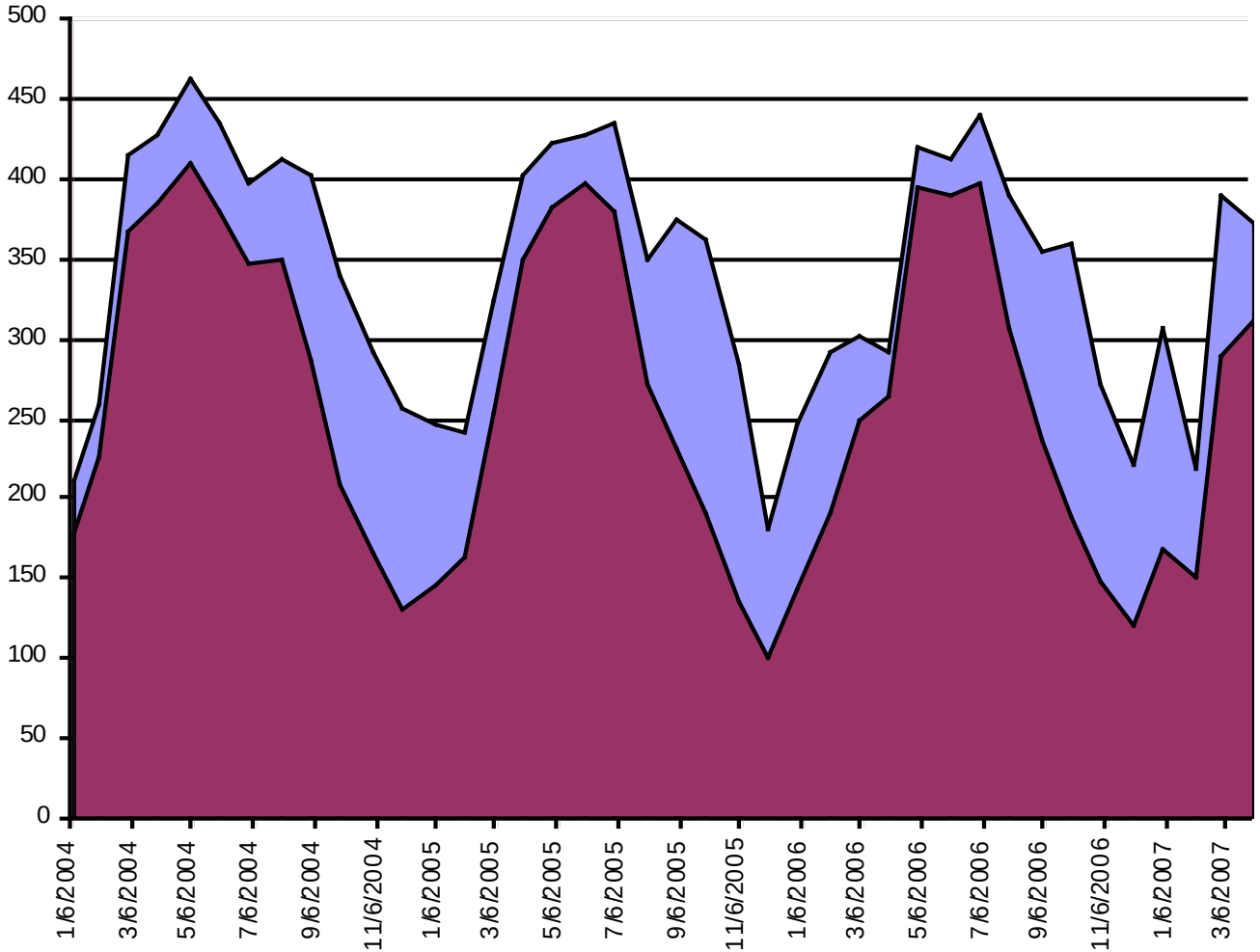
Uni-Solar

Thin Film a-Si Laminates

Uni-Solar/SIT

Product Advantage –

More electricity for the same rated power



Up to 20% more electricity than crystalline PV at same cost

Source: PV System Performance
Santa Cruz, CA

Uni-Solar

Thin Film CIGS Manufacturing

Global Solar

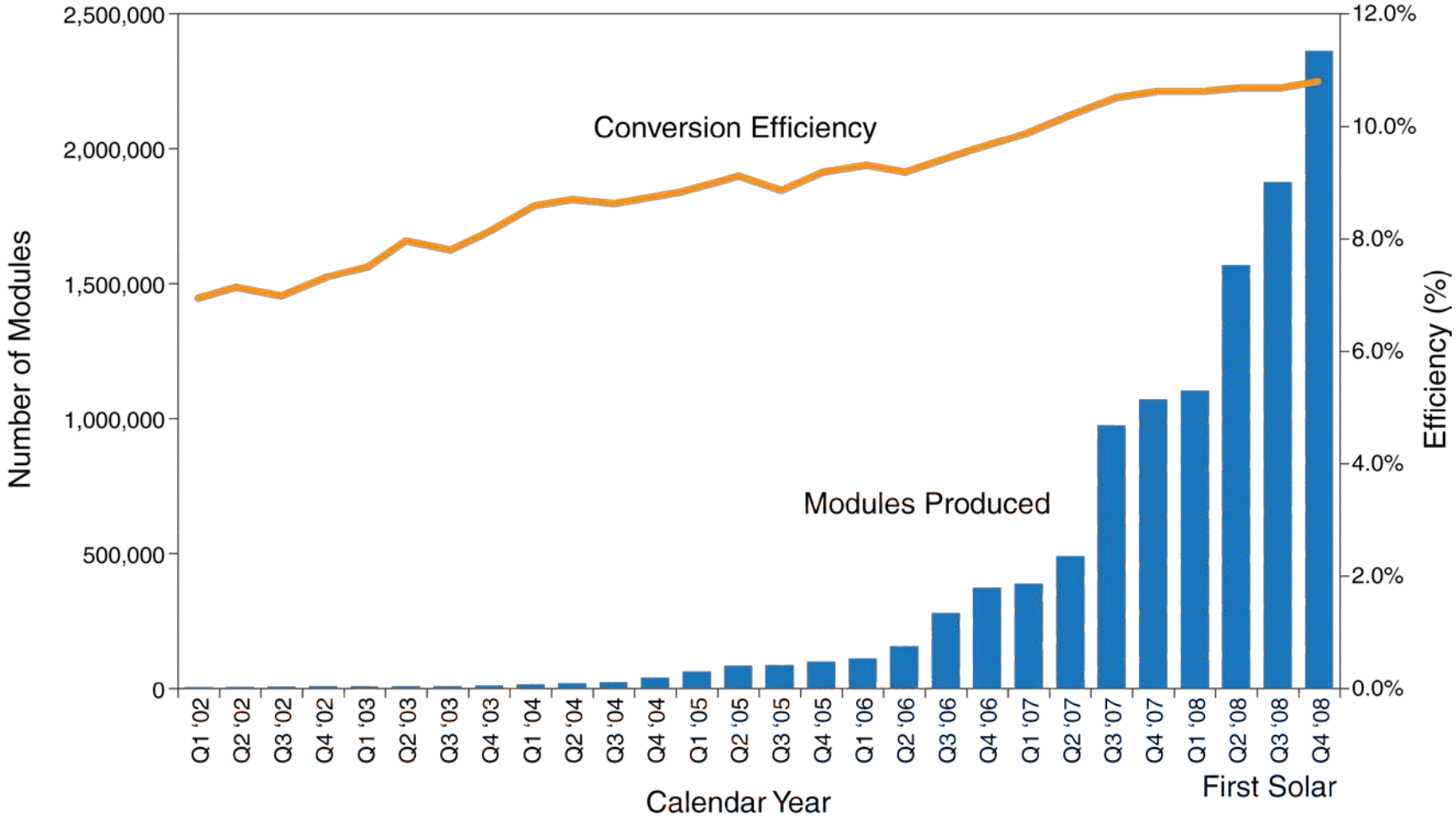
Thin Film CIGS Manufacturing

Ascent Solar

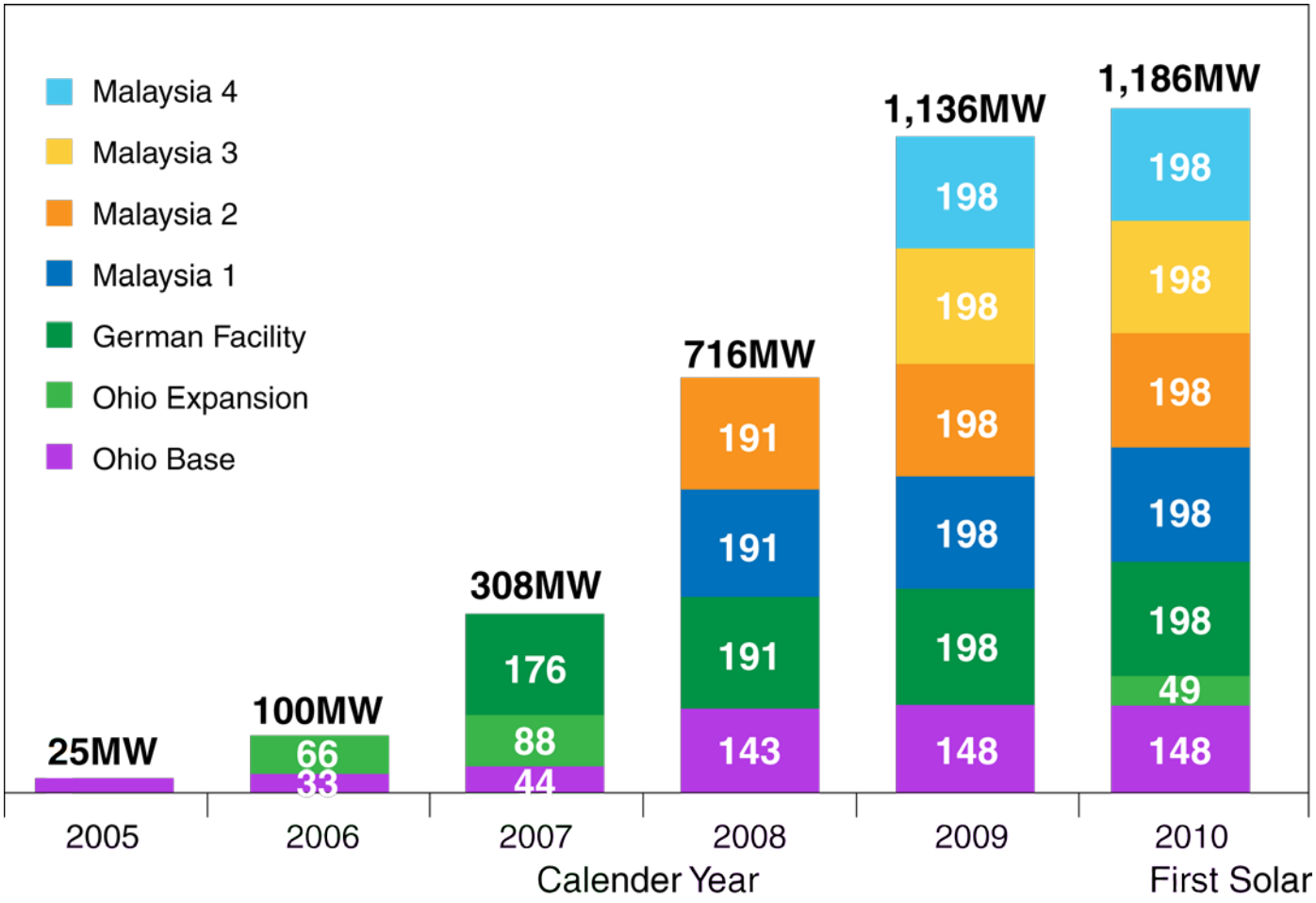
>200 MW – Thin Film CdTe Manuf.–USA

First Solar

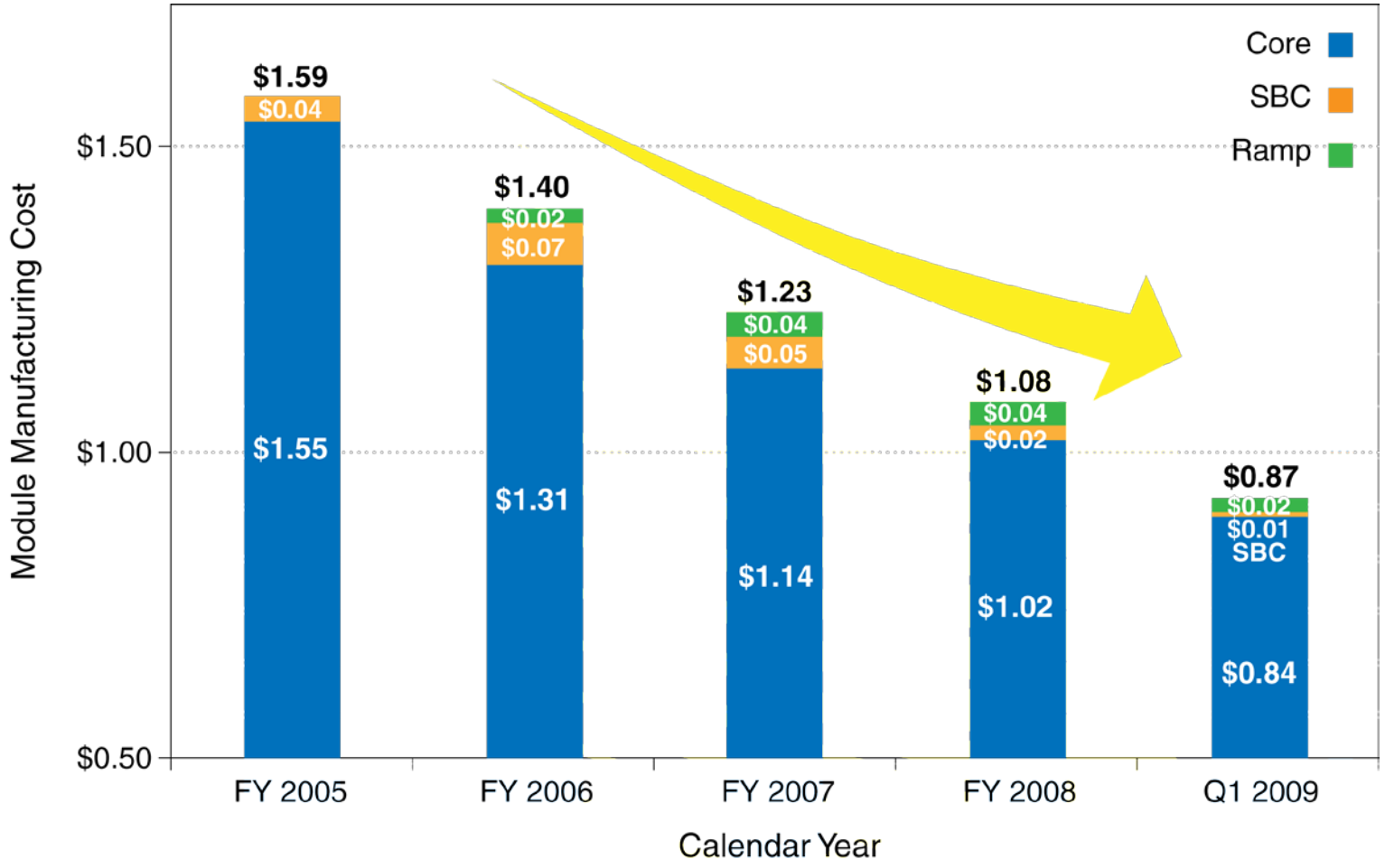
Conversion Efficiency vs Calendar Year



Largest Global Module Manufacturer



Lowest Module Manufacturing Cost



53 MW – Thin Film Solar Farm

First Solar / Juwi Solar

Lessons Learned

- Addressed key technical research issues in the respective thin film PV technology area
- Intellectually stimulating discussion during meeting & planning sessions for future productive meetings
- Research topics decided by team members by consensus
- Meeting timeline of ~1 year appears to be optimum
- Meeting minutes has great value for future references
- Rotating meeting locations helped broaden perspective of the various capabilities and lab facilities

Quote

“United Solar Ovonic (USO) has been participating in many programs sponsored by DOE/NREL for more than two decades. One example is Thin Film PV Partnership Program. I consider this program exemplary where we have worked with the academia and NREL to address key issues that have resulted in substantial reduction in cost of solar electricity. Such achievements are possible only when the best brains from diverse background address issues that are intellectually stimulating, but also have a profound impact on DOE and industry objectives. I applaud DOE/NREL for pioneering such a program.”

Subhendu Guha, Ph.D.
Chairman
United Solar Ovonic

Quote

For over twenty years the CdTe Team provided a framework that brought together researchers with a wide variety of perspectives, levels of experience, technical capabilities and objectives but who were all motivated by the goal of development of thin film CdTe PV technology. Consistent with the philosophy of NREL's management of their thin film CdTe PV subcontracts, overall direction of Team activities focused on issues of importance to industrial members. Thus while the scope of activities included for discussion was broad enough to include almost any experimental, theoretical or analytical work related to CdTe, the focus of discussion was always on how these activities might impact commercialization of the thin film technology.

Within industry our in-house activities were narrowly focused on optimization of our manufacturing process and typically did not allow us time to delve into the underlying science. Working with the CdTe Team academic and government researchers to investigate areas of interest to us. Equally important was the opportunity that each CdTe Team meeting provided to learn about innovative and diverse ideas, investigations and analyses of CdTe films and devices. The CdTe Team meetings were both the most relevant and intellectually stimulating technical meetings that I attended.

While it is not possible to quantify, I believe that the CdTe Team and NREL's consistent, broad focus on technical issues important to CdTe PV manufacturing was an important part of the ultimate success of that industry.

Peter V. Meyers, Ph.D.
Chief Scientist (Retired)
First Solar

Summary

- Excellent interaction between academia, industry and national labs
- Best U.S. brain power in one single room in the respective thin film PV technology area,
  but do not micro-manage
- Intellectually stimulating discussion among the various team members
- Help create the #1 companies in a-Si (Uni-Solar), CdTe (First Solar), and CIS (Global Solar)
- Created few thousand high paying “good” jobs in the U.S.
- Excellent “ROI” for U.S. tax payers