Si Thin-Film Photovoltaics Program in the U.S.

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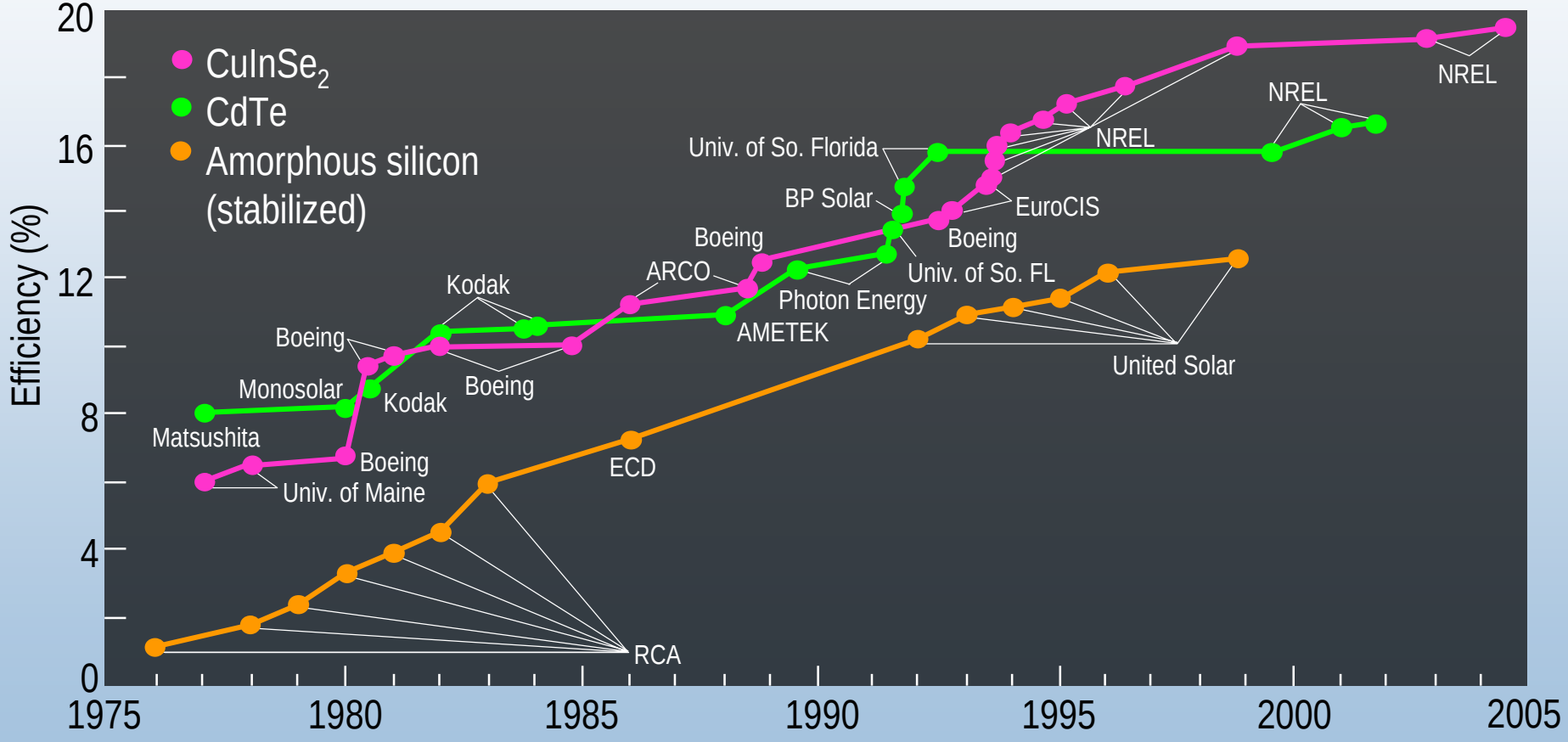
Presentation Outline

- History
- Results of research activities
- Competing PV Technologies
- Outlook

The Best One-of-a-Kind Laboratory Cell Efficiencies for Thin Films
(Standard Conditions)



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History

1980-1992: Amorphous Silicon Research Project (a-Si subcontracts and in-house research)

1992-2007: Thin Film Partnership (subcontracts for all Thin-Film PV technologies, since 2005 one in-house group for wafer and film Si)

>2007: SAI technology partnerships to accelerate commercialization + new (“incubator”) programs under development

a-Si:H history

- Much excitement since about 1980, 10% module product goal.
- Commercial activity that, from 1995 to 2005, lost PV market share, commercial performance increased from 3% -5% stabilized module efficiency (1990ies) to 4% to 7% (~2005)
- Significant R&D effort on physics and material science of a-Si:H

a-Si:H history

- Initial hope to eliminate S/W degradation did not materialize, since 1991 NREL program focuses on stabilized cell and module efficiency.
- Much effort on improving stabilized material parameters, little progress with stabilized efficiency
- While introduced in the mid-1990ies, “micromorph” (a-Si:H/nc-Si multijunctions) did not receive much US attention until about 2001

a-Si:H history

- Much work at NREL on light-soaking and stabilization of modules to reconcile early differences observed in in-door light-soak experiments and out-door exposure (1991-2002)
- Since 2002, work on micromorph Si film cells and on AstroPowers high-T recrystallized films.
- The NREL Thin Film Partnership viewed a-Si/nc-Si, CIGS, and CdTe PV technologies as equally important and evenly allotted resources (in earlier years, a-Si had a somewhat larger than 1/3 support)

a-Si:H history

- In 2002, subcontracts to (a) MVSystems, (b) EPV, (c) Uni-Solar, and (d) AstroPower addressed Si-film solar cell performance.
- Reduced budgets in 2005 forced termination of all but Uni-Solar's nc-Si subcontracts (also, AstroPower's large-grain Si film), most subcontractors did not meet promised stabilized efficiency milestones
- Major findings are worth-while to be summarized

nc-Si:H (Si-film) summary

1. Cell performance is extremely sensitive to “seeding” and cell structure (as first suggested in 1999 by Carius et al., Julich), cell results were perhaps less consistent than a-Si:H (a-SiGe:H) results
2. Best nc-Si cells use smaller grain mixed phase (“near the edge”) absorbers (while best a-Si:H cells are made at conditions just short of turning nc-Si)
3. Large grain AstroPower cells did not significantly out-perform nc-Si cells.

Are there limits to understanding?

- Materials with different chemistry and grain structure can result in both high and low efficiency cells! (So what is to be learnt from studying the particular details of a specific device?)
- As often the case is being made that “much more” is known about the silicon semiconductor compared to CIGS and CdTe, why then are those solar cells and modules generally of higher efficiencies than devices made from thin film silicon (<50 µm-thick)?

A Rigorous Scheme for Comparing the Near-Term Potential of Different PV Module Technologies

- We needed to asses real efficiency numbers, knowing that champion cell results and commercial product are well documented.
- Define the c/c ratio as the ratio between verified (stabilized) champion cell efficiency and commercial product efficiency
- Assume that at some point in the future, c/c values of 0.8 will be achieved for all technologies
- Project cost effectiveness ($/$W_p$) assuming that a thin-film module will avoid Si wafer cost, otherwise cost the same as Si modules.

Web Survey of ("best") Commercial Modules

Eff. (%)	Module	T.coeff (%P/°C)	Technology	c/c-ratio
17.7	SunPower SPR210	-0.38	FZ-Si, 'point contact'	72%
17.0	Sanyo HIP-200BE3	-0.30	CZ-Si, 'HIT'	69%
15.1	BP7190	-0.5	CZ-Si, 'PERL'	61%
14.2	Kyocera KC200GT	Only for Voc	MC-Si	67%
14.2	SolarWorld SW 185	Only for Voc	CZ-Si	67%
13.4	SolarWorld SW 225	Only for Voc	MC-Si,	64%
13.2	Schott ASE-320-DGF/50	-0.47	MC-Si,	63%
12.8	Sharp ND-208-U1	not given	MC-Si	61%
11.0	WürthSol. 11007/80	-0.36	CIGS	56%
9.4	First Solar FS-267	-0.25	CdTe	57%
8.5	Sharp NA-901-WP	Not given	a-Si/nc-Si	70%
6.3	Mitsubishi H. MA100 T2	-0.2	a-Si (1-j)	64%
6.3	Uni Solar PVL-136	(-0.21)	a-Si (3-j)	52%
6.3	Kaneka T-SC	Not given	a-Si (1-j)	64%

Future commercial module performance based on today's champion cell results and a c/c-ratio of 80%

Technology	Future commercial performance	Relative Performance (s.p. Si =1)	Relative-cost/relative-performance (*40*% thin film cost advantage)
Silicon (non-stand)	19.8%	1.18	0.85 (highly competitive)
Silicon (standard)	17.0%	1.00	1.00 (reference)
CIS	15.6%	0.92	0.65 (highly competitive
CdTe	13.2%	0.78	0.77 (highly competitive)
a-Si (1-j)	8.0%	0.47	1.28 (not competitive)
a-Si (3-j) (or a-Si/nc-Si)	9.7%	0.57	1.05 (about the same)

Conclusions:

- Champion cell results can predict commercial product performance
- Without a 15% efficient total-area stabilized cell, there will be no commercial 10% low-cost module product.
- a-Si/nc-Si will need a breakthrough to be competitive with competing technologies in the long run
- Near term, all technologies are competitive, thin films with efficiencies >9% will lead the way towards lower module prices

Module Reliability and Customer Acceptance

(a) Long-term module performance

(b) Customer acceptance issues (e.g. voltage)

(c) Optimized packaging schemes

NREL-led team working on these issues

Reliability and Package

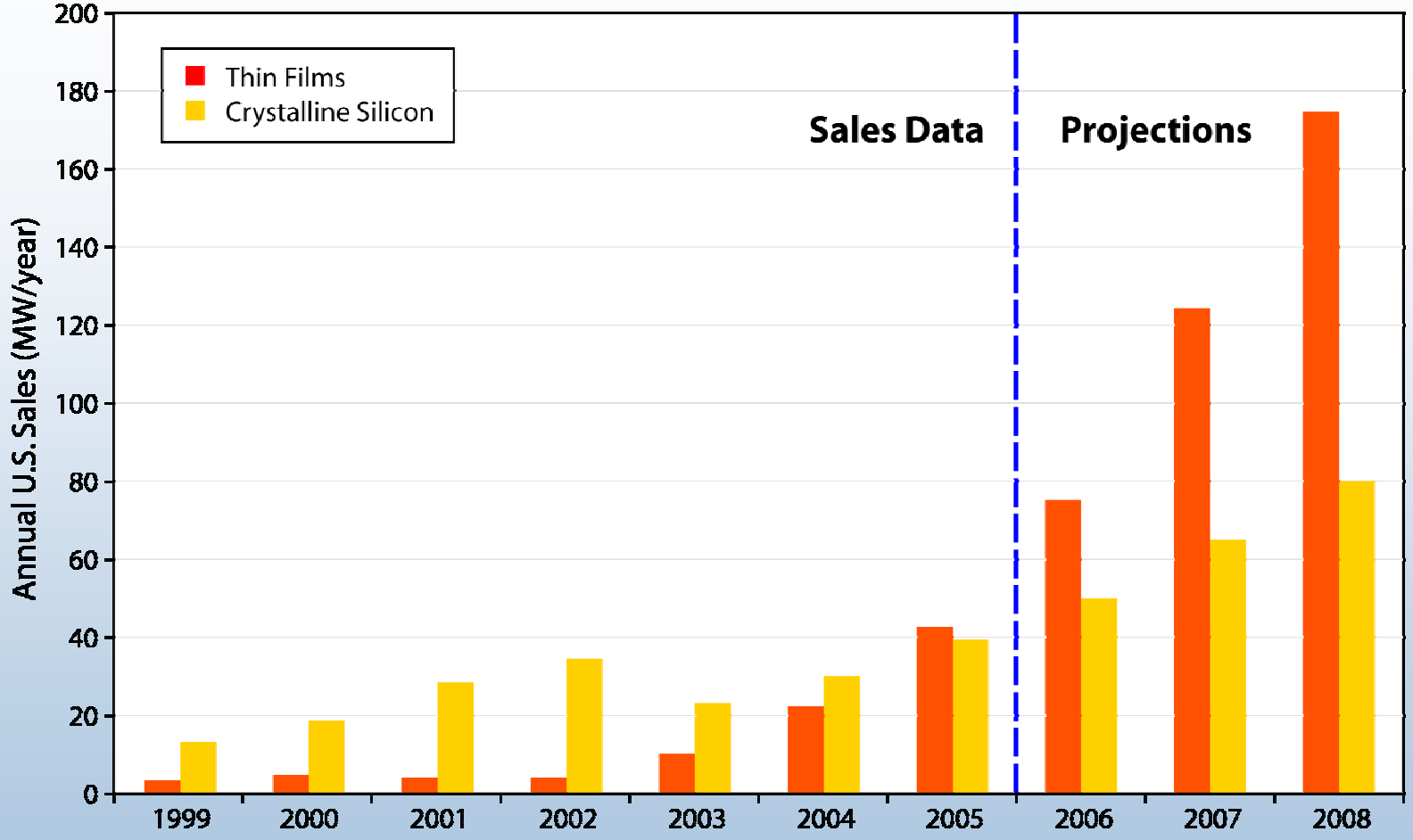
- CIGS and CdTe were found to be more moisture sensitive, often require better module encapsulation schemes than x-Si (or amorphous Si) PV modules
- Improved module package schemes allowed CIGS and CdTe modules to pass the “damp heat” test (1000-hour exposure at 85 ^{o}C and 85% relative humidity)
- Processing affects the performance during “stressing,” — light exposure at elevated (typically, 65 to 100 ^{o}C device temperature) in various atmospheric ambients
- Si thin-film modules are both furthest developed and pehaps least critical to last for >20 outdoors

Hot & Humidity Testing

FSEC

Commercialization and Systems

- Thin-Film Modules are used for some large field installations in Germany
- Module cost per Watt should be ~70% of x-Si modules, for installed system costs of ~85 – 90% of x-Si systems
- Glass-to-glass (foil) laminates most suited for large field installations



US-owned, US manufactured modules by technology, crystalline Si and Thin Films (incl. a-Si) 1999-2008

Conclusions

- Many issues how thin-film solar cells work remain unresolved, requiring further fundamental R&D effort
- Commercial thin-film PV module production reached 29% in 2005 in the U.S., indicating much more rapid growth than crystalline Si PV
- Commercial module performance is increasing based on current knowledge. Today's R&D will lead to future product improvement
- Stability of thin-film modules is acceptable (≤ 1% per year power loss) if the right manufacturing processes are used for manufacturing