

# Polycrystalline Thin Film Photovoltaics: From the Laboratory to Solar Fields

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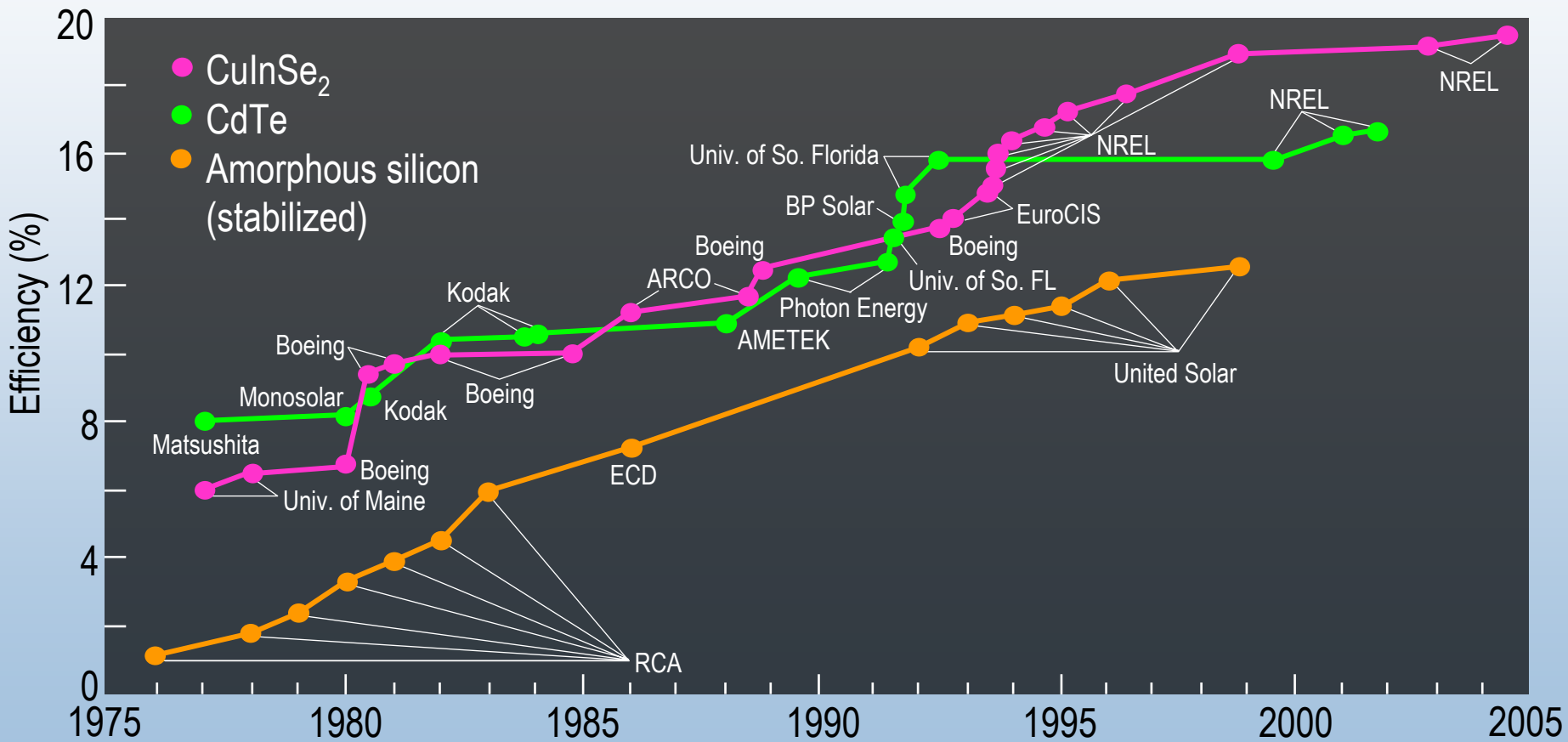
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# Presentation Outline

- Scientific Base for Polycrystalline Thin Film Photovoltaics
- CIGS Technology
- CdTe Technology
- Commercialization

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



# Why is Better Fundamental Understanding Required and Helpful?

- (a) For better process control and optimization
- (b) Understanding the limits of a given process

# Why better understanding?

- Not only an academic issue, but also a requirement for achieving maximum commercial product performance and yield
- Assist in selecting necessary processing for best performance (when to “tweak” and when to upgrade a process)
- Realistic assessment of ultimate performance of a given technology

# Activities and Tools

- In-house characterization at NREL
- New characterization group using surface and “near-surface” analyses at UNLV
- Much work on the effect of micro- and nano-non-uniformities (Y. Yan at NREL, V. Karpov at U. Toledo)

# 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  $\mu\text{m}$ -thick)?



# CIGS PV Technology R&D

- Thin ( $<1 \mu\text{m}$ ) -absorber cells
- (Cd)ZnS(O,OH) junction layers
- Alternative fabrication methods (“inks” or “paints,” –non-vacuum) hybrid deposition, selenization and sulfurization
- Wider bandgap  $\text{CuGaSe}_2$  or  $\text{Cu}(\text{In},\text{Ga})\text{S}_2$

| <b>Area<br/>(cm<sup>2</sup>)</b> | <b>V<sub>OC</sub><br/>(V)</b> | <b>J<sub>SC</sub><br/>(mA/cm<sup>2</sup>)</b> | <b>FF<br/>(%)</b> | <b>Effic.<br/>(%)</b> | <b>Comment</b>  |
|----------------------------------|-------------------------------|---|-------------------|-----------------------|---|
| <b>0.410</b>                     | <b>0.6975</b>                 | <b>35.078</b>                                 | <b>79.52</b>      | <b>19.5</b>           | <b>Standard Champion<br/>CIGS cell (NREL)</b>         |
| <b>0.408</b>                     | <b>0.7052</b>                 | <b>35.515</b>                                 | <b>77.90</b>      | <b>19.5</b>           | <b>CdZnS(O,OH) buffer<br/>(NREL)</b>                  |
| <b>0.402</b>                     | <b>0.6698</b>                 | <b>35.112</b>                                 | <b>78.78</b>      | <b>18.5</b>           | <b>ZnS(O,OH) buffer<br/>(NREL)</b>                    |
| <b>0.409</b>                     | <b>0.6782</b>                 | <b>31.93</b>                                  | <b>79.20</b>      | <b>17.1</b>           | <b>1.1 μm CIGS<br/>(NREL)</b>                         |
| <b>0.5</b>                       | <b>0.774</b>                  | <b>21.6</b>                                   | <b>73.7</b>       | <b>12.3</b>           | <b>Cu(In,Ga)S<sub>2</sub><br/>champion (HMI)</b>      |
| <b>0.409</b>                     | <b>0.8305</b>                 | <b>20.88</b>                                  | <b>69.13</b>      | <b>11.99</b>          | <b>“sulfurized”<br/>Cu(In,Ga)S<sub>2</sub> (FSEC)</b> |

# New Buffer Layers

- CdZnS and ZnS junction cells have achieved champion level cell performance
- Even the ZnS junctions are best when using “wet” chemical bath deposition (CBD) processes
- All high performance junction material are found to have very high electrical resistivity

# CIS R&D Focus

- Since champion efficiency cells were achieved by co-evaporation, this seems the R&D deposition method of choice, would more support of commercial processes be helpful?
- Industry also uses selenization/sulfurization (Shell Solar), hybrid processes (EPV), and non-vacuum “ink” or “paint” processes (ISET and Nanosolar)

# CdTe PV Technology R&D

- Micro non-uniformity of CdTe films & its impact on device performance
- Thin CdTe absorber layers
- Interdiffusion at the CdS/CdTe interface,
- (Vapor) CdCl<sub>2</sub> heat treatments
- Role of Cu “doping” during back-contacting
- Can  $V_{OC}$  be increased to above 850 mV without loss in  $J_{SC}$  and FF?

# “Champion” Modules

(\* = NREL confirmed)

| Company          | Device | Aperture Area (cm <sup>2</sup> ) | Eff. (*NREL confirmed) | Power (W) | Date  |
|------------------|--------|----------------------------------|------------------------|-----------|-------|
| Würth Solar      | CIGS   | 6500                             | 13.0                   | 84.6      | 06/04 |
| Shell Solar GmbH | CIGSS  | 4938                             | 13.1                   | 64.8      | 05/03 |
| Shell Solar      | CIGSS  | 3626                             | 12.8*                  | 46.5*     | 03/03 |
| Showa Shell      | CIGS   | 3600                             | 12.8                   | 44.15     | 05/03 |
| Shell Solar      | CIGSS  | 7376                             | 11.7*                  | 86.1*     | 10/05 |
| Global Solar     | CIGS   | 8390                             | 10.2*                  | 88.9*     | 05/05 |
| First Solar      | CdTe   | 6623                             | 10.2*                  | 67.5*     | 02/04 |

# 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 °C and 85% relative humidity)
- Processing affects the performance during “stressing,” — light exposure at elevated (typically, 65 to 100 °C device temperature) in various atmospheric ambients



# Reliability and Package

- To study cell/cell-interconnect/package interactions, it is planned to “stress” minimodules
- In CdTe cells, the details of the entire cell process as well as the details of back-contacting affect potential stability
- Warranties up to 25 years (80% of rated power guaranteed) now available from some manufacturers (First Solar)

# 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 laminates most suited for large field installations

# Commercialization and Systems

PV Market segments:

- (1) Large Fields
- (2) Retail Modules
- (3) BIPV

Thin Film Modules have addressed all applications, but manufacturers need to continue to improve modules to meet specific market's needs

# Polycrystalline Thin Film PV: Global Solar Installations

| Location               | Material | Size (kW) | Date        |
|------------------------|----------|-----------|-------------|
| Dimbach, Germany       | CdTe     | 1,400     | 2004 - 2005 |
| Reussenkoge, Germany   | CdTe     | 1,040     | 2005        |
| Fellber, Germany       | CdTe     | 800       | 2005        |
| Sinzheim, Germany      | CdTe     | 800       | 2005 - 2006 |
| Tepfhelm, Germany      | CdTe     | 778       | 2005        |
| Springerville, AZ, USA | CdTe     | 500       | 2001 - 2003 |
| Florsheim, Germany     | CdTe     | 440       | 2005        |
| Camarillo, CA, USA     | CIS      | 245       | 2003        |

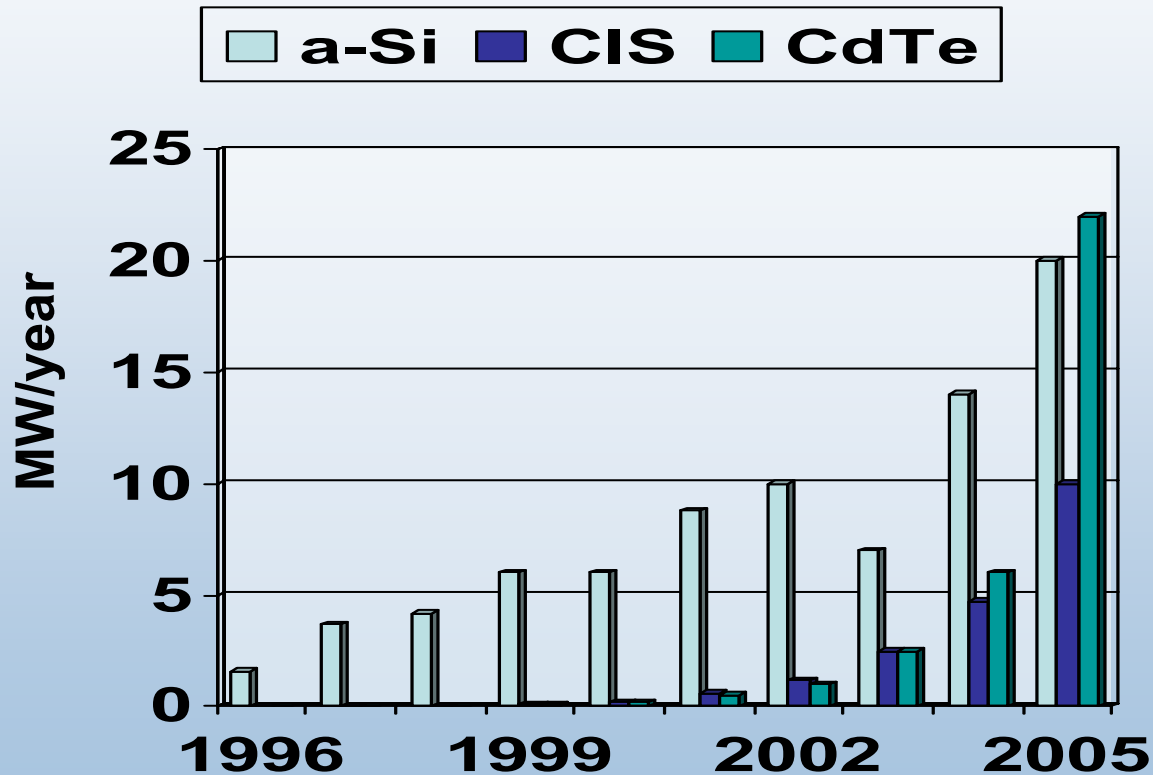
# Large Solar Field

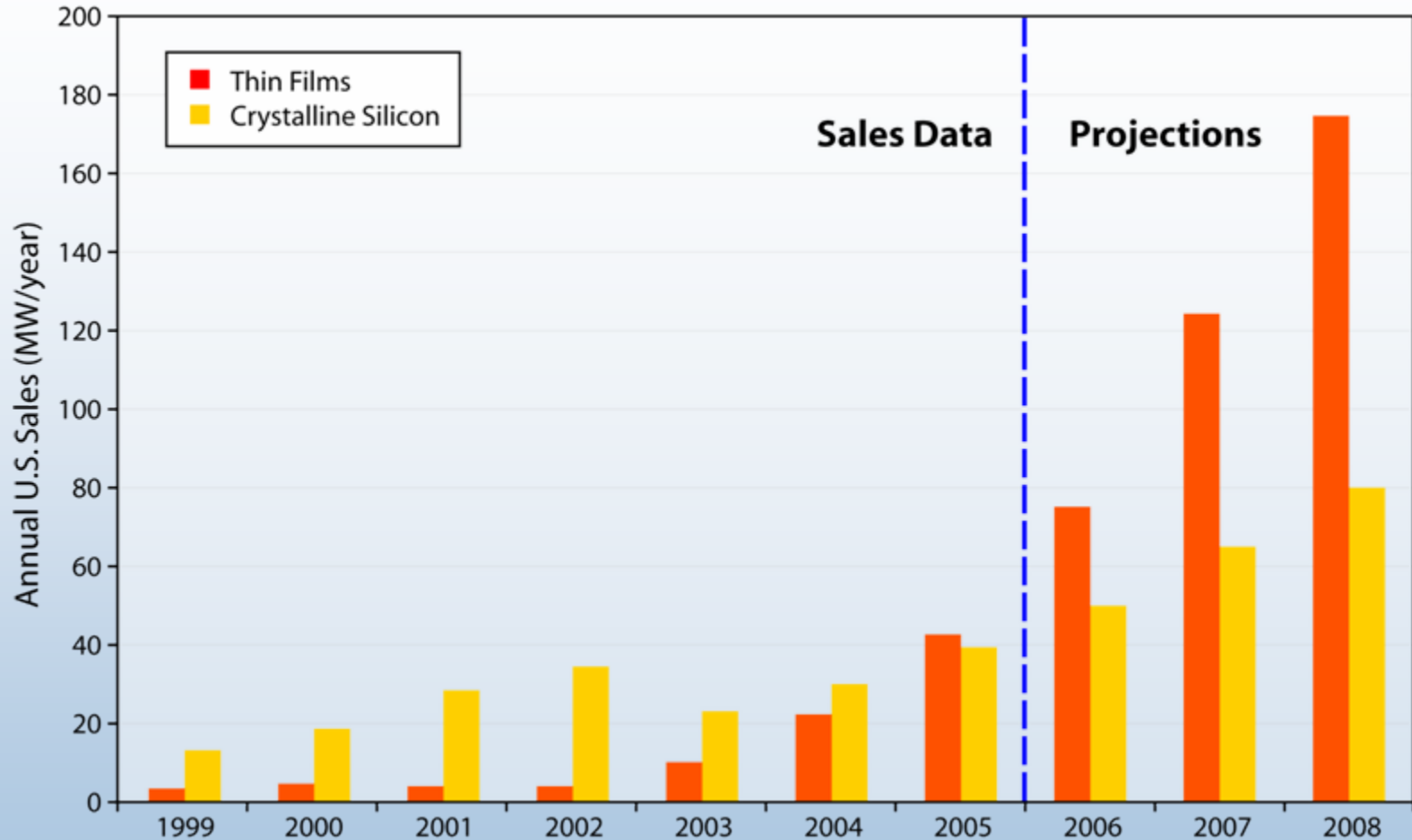
First Solar 1,425 kW<sub>p</sub> System Deponie Sinzheim, Germany



# U.S. Thin Film Production

(Figure from 31<sup>st</sup> (01/2005) IEEE PVSC presentation)





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. More R&D will lead to further improvement
- Stability of thin-film modules is acceptable ( $\leq 1\%$  per year power loss) if the right manufacturing processes are used for manufacturing