2.626 Fundamentals of Photovoltaics
Fall 2008

Thin Films: Materials Choices & Manufacturing

Lecture 11 – 2.626

Tonio Buonassisi

General Matters

- Exam
- Homework #2
- Class Project next steps

Further Reading

- Visit http://www.knovel.com from an on-site computer (or with certificates).
- Search for “Handbook of Photovoltaic Science and Engineering”.
- Suggested Chapters:
  - 12: Amorphous Silicon Thin Films
  - 13: CIGS Thin Films
  - 14: CdTe Thin Films
  - 15: Dye-Sensitized Solar Cells
- Harvard Folks: If you have difficulty accessing this content, please email Sarah or me.

Thin Films: General Issues

Diversity in the PV Market

http://peswiki.com/images/8/86/Spheral_solar_panel_95x95.jpg

Fig. 1 in Takamoto, Tatsuya, et al. “Over 30% efficient InGaP/GaAs tandem solar cells.” *Applied Physics Letters* 70 (January 20, 1997): 381-383.

Spheral Solar

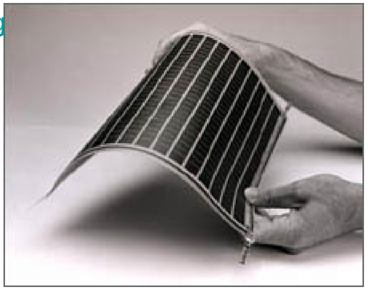
http://site.novatechgadgets.com/evtechfeat.jpg

http://www.stangl.de/typo3temp/pics/691aeb319e.jpg

Silicon Ribbon

Heterojunction Cells

Copper Indium Diselenide (CIS)



Courtesy EERE.

Amorphous Silicon

http://www.atp.nist.gov/eao/sp950-1/astropw1.jpg

http://www.iea-pvps.org/ar/ar00/images/aus03.jpg

http://www.ajeal.net/english/wp-content/uploads/solar-panel-cost.jpg

Dye-sensitized Cells

Silicon Sheet

Cadmium Telluride

http://www.triplepundit.com/nanosolar.jpg

Hybrid (nano)

Future technologies must consider:

- **Cost ($/kWh)**
- **Resource availability**
- **Environmental impact**

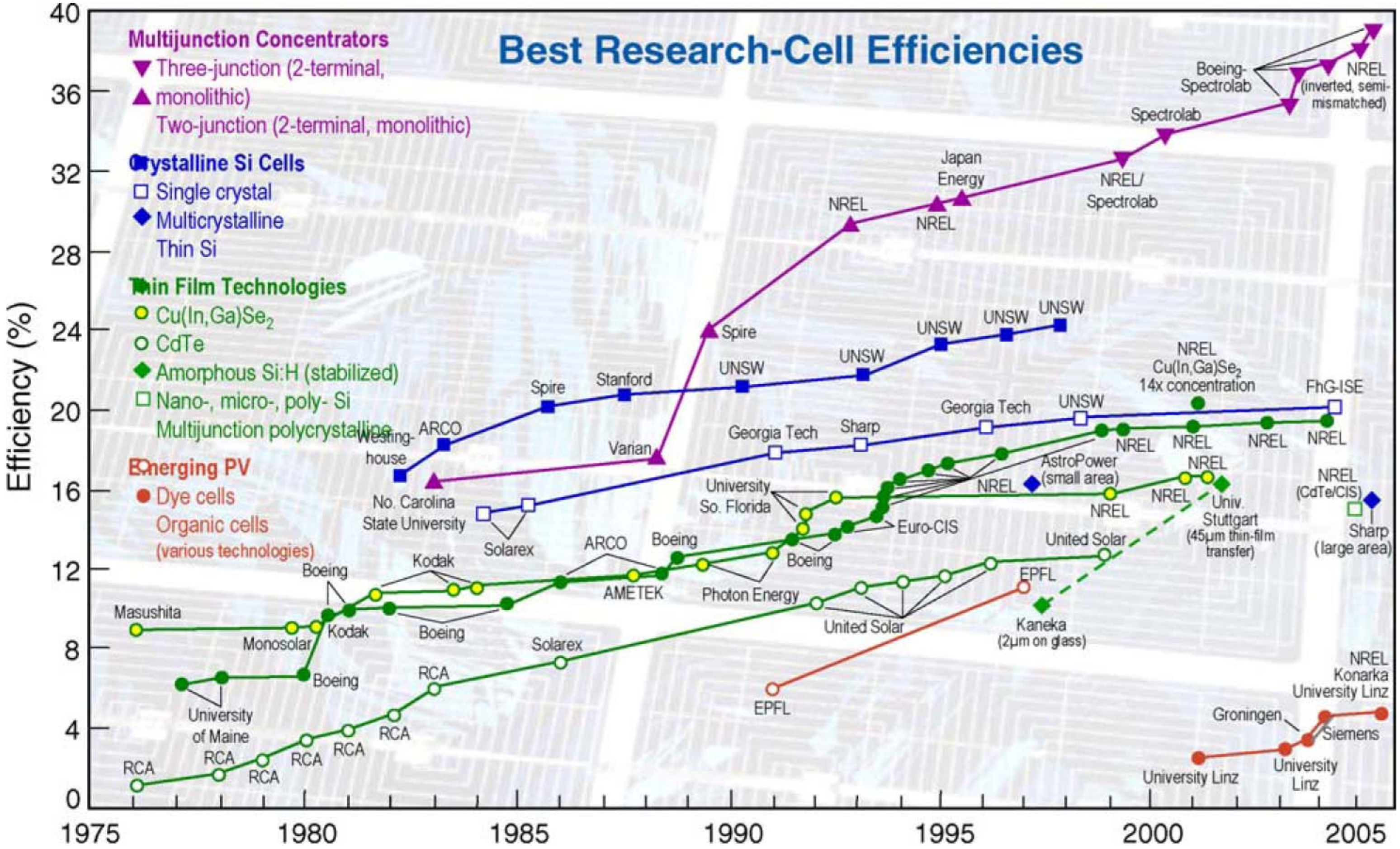
http://electronicdesign.com/Files/29/11527/Figure_01.jpg

http://www.livescience.com/images/0412_solar_panels_03.jpg

SunPower Back-contacted

Organics

Record laboratory efficiencies of various materials



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L.L. Kazmerski, Journal of Electron Spectroscopy and Related Phenomena 150 (2006) 105–135

NOTE: These are record cell efficiencies under ideal conditions (25°C, ~1000 W/m^2)! Actual commercially-available silicon solar cells are typically 14-17% efficient. Modules are typically around 11-13%.

Thin Films

Advantages

- 1 µm layers ➔ less material used ➔ potential cost decrease.
- Potential for lower thermal budget ➔ potential cost decrease.
- Potential for roll-to-roll deposition on flexible substrate.
  - Technology transfer with TFT, flat panel display industry.
- Good for BIPV applications.
- Radiation hardness.

Disadvantages

- Lower efficiencies ➔ potentially larger module costs.
- Potential for capital-intensive production equipment.
- Potentially scarce elements sometimes used.
- Spatial uniformity a challenge during deposition.

Thin Films

Advantages:

Roll-to-roll deposition of µm-sized layers ➔ potentially high throughput, large-area deposition, and cheap.

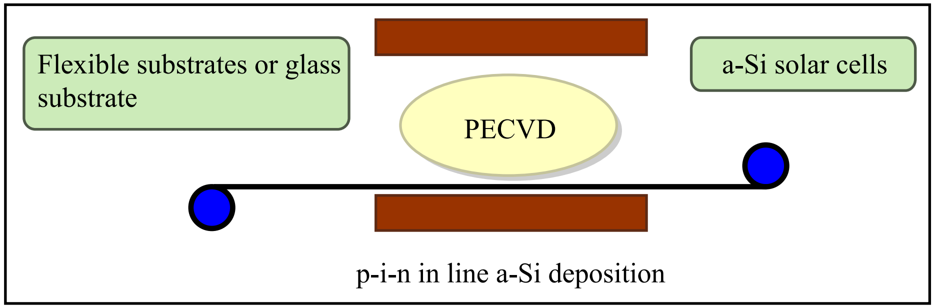
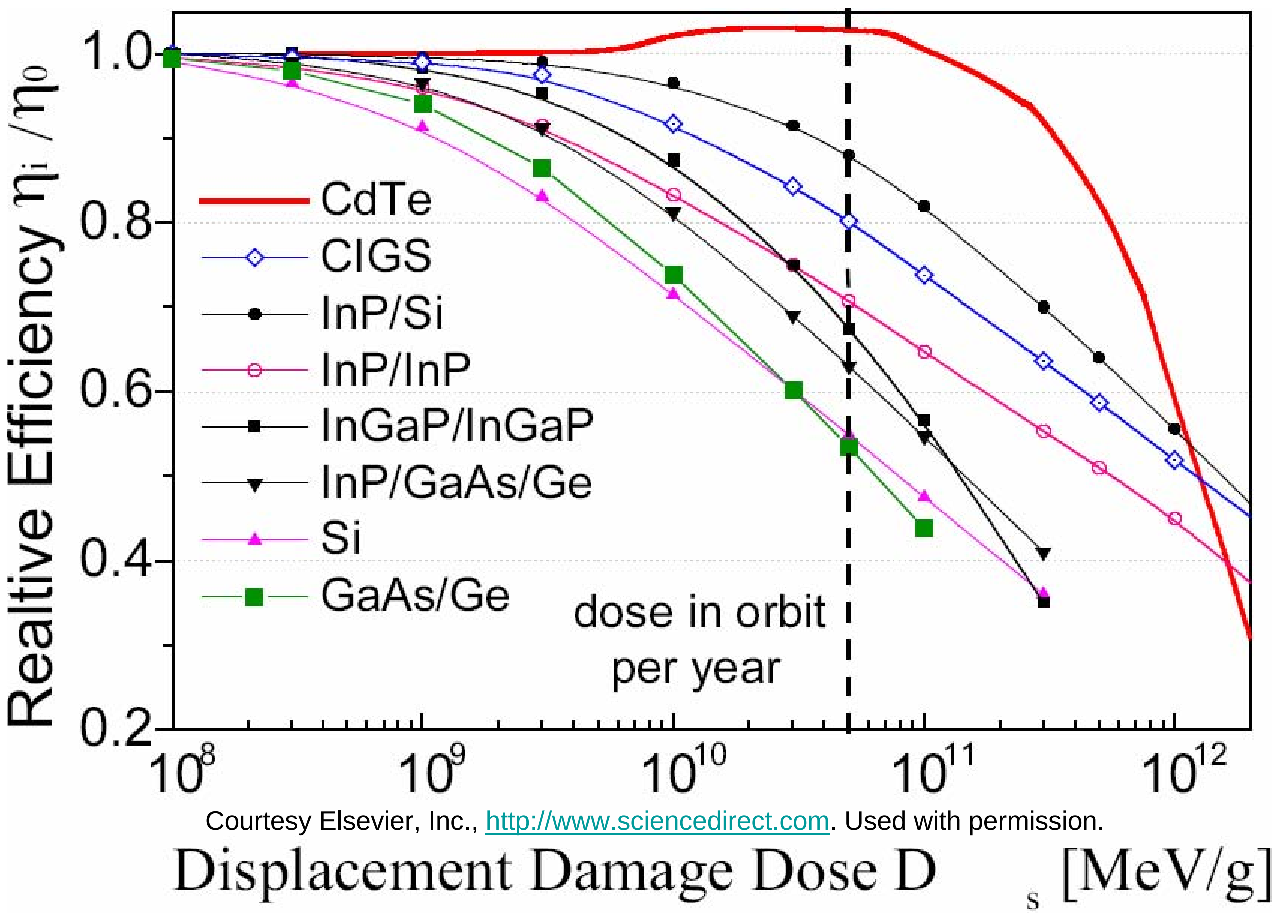


Figure by MIT OpenCourseWare.

Building-integrated solutions

http://www.carbonfreegroup.com/images/photovoltaic_files/solar-shingle.jpg
http://www.inhabitat.com/images/bipv1.jpg

Radiation hardness of different compounds



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‚Master data' by courtesy of S.Messenger, G. Summers

Space payloads cost ~\$1400–\$6000/pound (~\$2866–\$13228/kg) ➔ Key parameter not \$/W. Instead, it's <u>W/kg</u> and <u>reliability</u>!

Grain Size and Efficiency

Images removed due to copyright restrictions.
Please see Fig. 1 and 2 in Bergmann, R. B.
“Crystalline Si thin-film solar cells: a review.”
Applied Physics A 69 (1999): 187-194.

R.B. Bergmann, *Appl. Phys. A* **69** (1999) 187

See also:
T.F. Ciszek, *J. Cryst Growth* **237-239** (2002) 1685

Heterostructures and Lattice Matching

To prevent interface recombination and achieve high carrier mobilities, atoms in the different layers must line up (adjacent hetero-epitaxial layers must be lattice matched). Otherwise, defects form at these interfaces.

An good example of a heteroepitaxial system is Ge / GaAs / InGaP / AlAs, in order of increasing bandgap.

Image removed due to copyright restrictions. Please see
http://www.tf.uni-kiel.de/matwis/amat/semi_en/kap_5/illustr/bandgap_misfit.gif
http://www.tf.uni-kiel.de/matwis/amat/semi_en/kap_5/illustr/materials.gif

http://www.sri.com/psd/apsl/images/zincbg.gif

Material Abundances

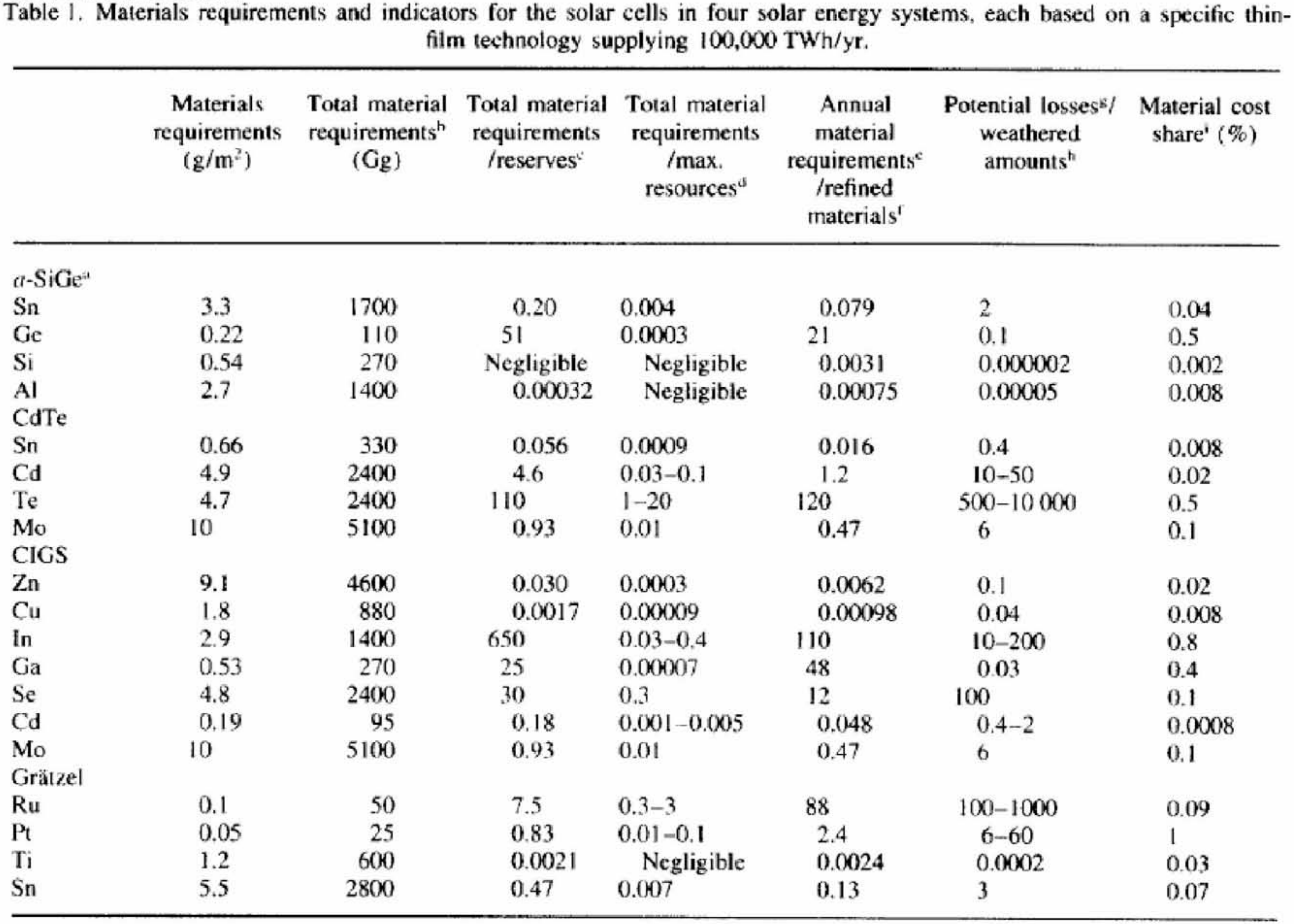


Table 1. Materials requirements and indicators for the solar cells in four solar energy systems, each based on a specific thin-film technology supplying 100,000 TWh/yr.

	Materials requirements (g/m^2)	Total material requirements[b] (Gg)	Total material requirements /reserves[c]	Total material requirements /max. resources[d]	Annual material requirements[e] /refined materials[f]	Potential losses[g]/ weathered amounts[h]	Material cost share[i] (%)
a-SiGe[a]							
Sn	3.3	1700	0.20	0.004	0.079	2	0.04
Ge	0.22	110	51	0.0003	21	0.1	0.5
Si	0.54	270	Negligible	Negligible	0.0031	0.000002	0.002
Al	2.7	1400	0.00032	Negligible	0.00075	0.00005	0.008
CdTe							
Sn	0.66	330	0.056	0.0009	0.016	0.4	0.008
Cd	4.9	2400	4.6	0.03–0.1	1.2	10–50	0.02
Te	4.7	2400	110	1–20	120	500–10 000	0.5
Mo	10	5100	0.93	0.01	0.47	6	0.1
CIGS							
Zn	9.1	4600	0.030	0.0003	0.0062	0.1	0.02
Cu	1.8	880	0.0017	0.00009	0.00098	0.04	0.008
In	2.9	1400	650	0.03–0.4	110	10–200	0.8
Ga	0.53	270	25	0.00007	48	0.03	0.4
Se	4.8	2400	30	0.3	12	100	0.1
Cd	0.19	95	0.18	0.001–0.005	0.048	0.4–2	0.0008
Mo	10	5100	0.93	0.01	0.47	6	0.1
Grätzel							
Ru	0.1	50	7.5	0.3–3	88	100–1000	0.09
Pt	0.05	25	0.83	0.01–0.1	2.4	6–60	1
Ti	1.2	600	0.0021	Negligible	0.0024	0.0002	0.03
Sn	5.5	2800	0.47	0.007	0.13	3	0.07

Courtesy Elsevier, Inc., http://www.sciencedirect.com. Used with permission.

B.A. Andersson et al., *Energy* **23** (1998) 407

http://www.nrel.gov/ncpv/enough_pv.html

Deposition Technologies

Images removed due to copyright restrictions. Please see
http://i236.photobucket.com/albums/ff105/sanjaykram/PDP_Large/PECVD_png.png

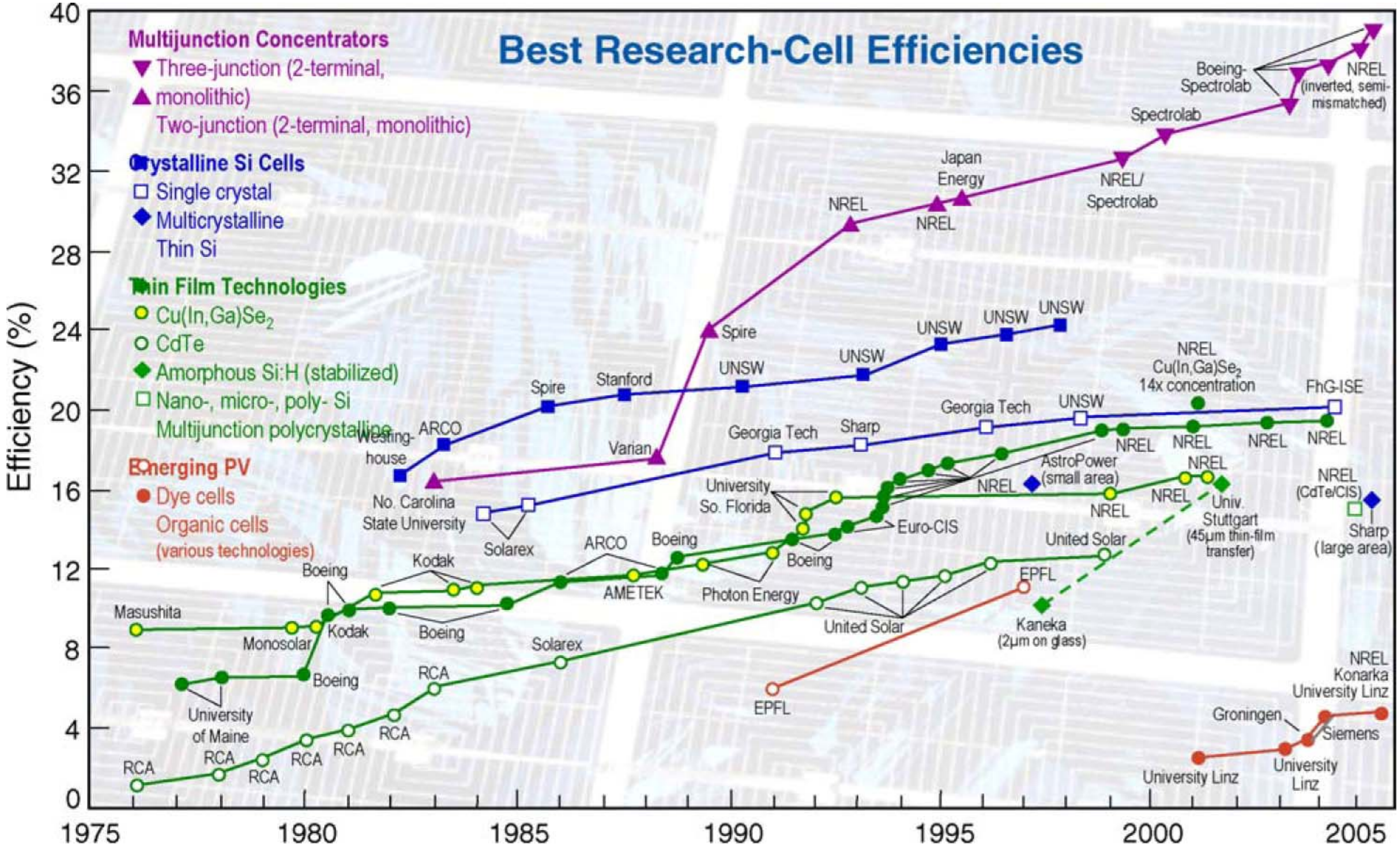
and any photo of chemical bath deposition, such as
http://www.cranfield.ac.uk/cds/departments/dassr/images/22179_lg_solar%20cbd%20growth%20of%20cds_580x200.jpg

Vacuum Based: Large capex

Non-Vacuum Based: Small(?) capex

Thin Films: Technology Choices

Record laboratory efficiencies of various materials



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L.L. Kazmerski, Journal of Electron Spectroscopy and Related Phenomena 150 (2006) 105–135

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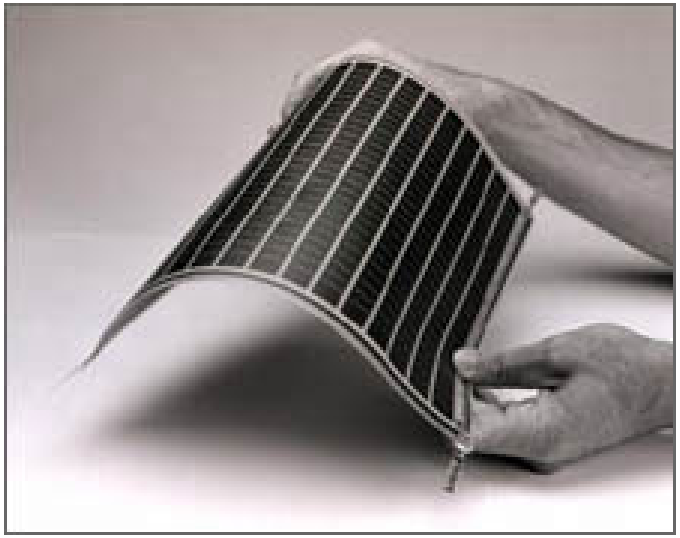
Amorphous Silicon (a-Si)



Courtesy EERE.

Image removed due to copyright restrictions. Please see Fig. 1 in Rech, B., and H. Wagner. “Potential of amorphous silicon for solar cells.” *Applied Physics A* 69 (1999): 155-167.

B. Rech and H. Wagner, *Appl. Phys. A* **69** (1999) 155

Advantages:

- Potentially very cheap, low-temperature.

Challenges:

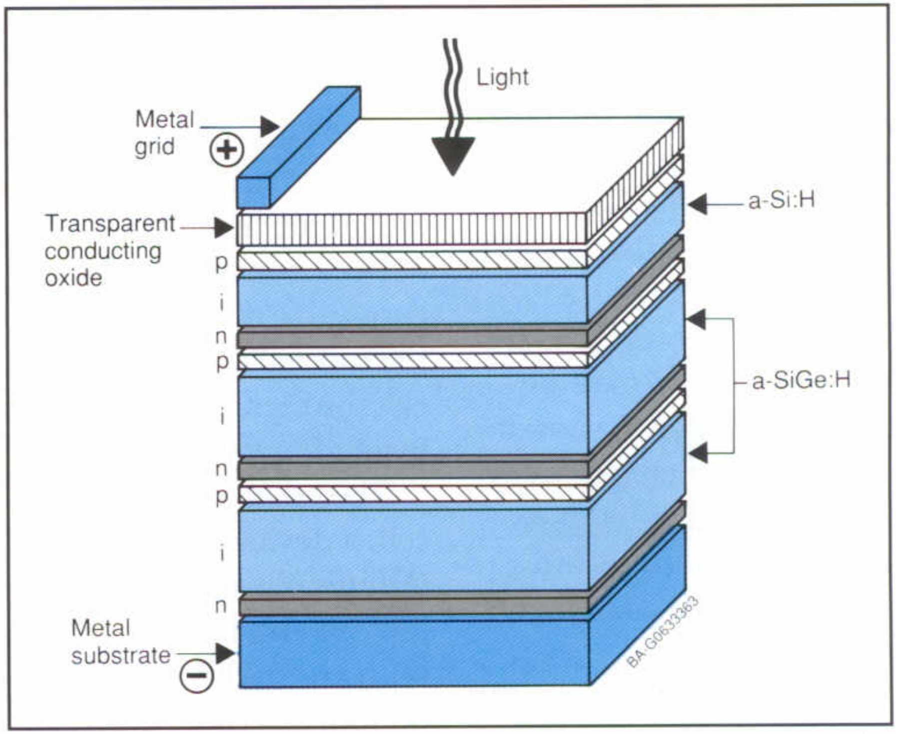
- Overcoming the Staebler–Wronski effect (SWE)
- Uniform (thickness, quality, grain size) film deposition.
- TCO expensive.
- Challenges to scaling

Energy Band Diagram of a-Si

Image removed due to copyright restrictions. Please see Fig. 2 in Rech, B., and H. Wagner. “Potential of amorphous silicon for solar cells.” *Applied Physics A* 69 (1999): 155-167.

B. Rech and H. Wagner, *Appl. Phys. A* **69** (1999) 155

a-Si heterostructures



Courtesy Sandia National Labs. Used with permission.

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B. Rech and H. Wagner, *Appl. Phys. A* **69** (1999) 155

http://www.sandia.gov/pv/images/PVFSC36.jpg

Staebler–Wronski effect (SWE)

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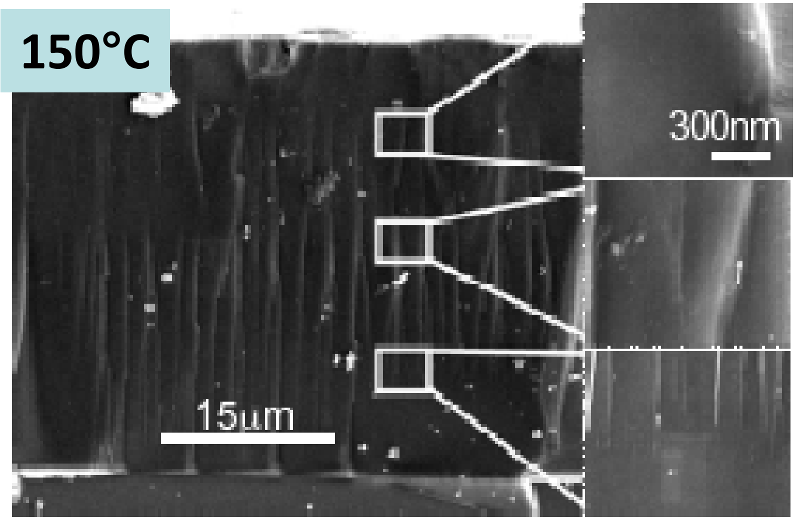
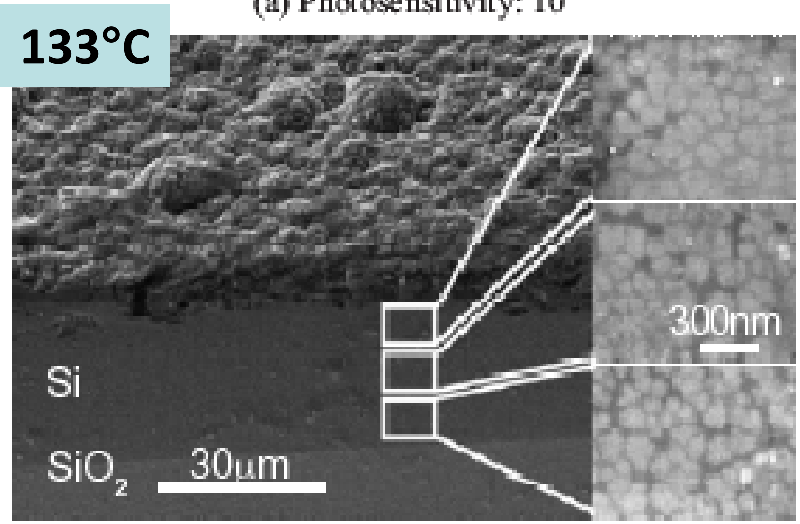
B. Rech and H. Wagner, *Appl. Phys. A* **69** (1999) 155

The a-Si (µ-Si) → nc-Si transition…

…is determined by deposition temperature…



(a) Photosensitivity: 10



(b) Photosensitivity: 1000

Fig.5 SEM images of the film deposited at different substrate temperature; (a) 150 and (b) 133°C.

http://www.plasma.t.u-tokyo.ac.jp/pict/silicon/Fig5.gif

Courtesy of Toyonobu Yoshida.
Used with permission.

…ambient gas content, and other factors.

Table removed due to copyright restrictions. Please see p. 5 in Wagner, Sigurd, David E. Carlson, and Howard M. Branz. "Amorphous and Microcrystalline Solar Cells." NREL (April 1999): CP-520-29586.

Image removed due to copyright restrictions. Please see Fig. 5 in Srinivasan, Easwar, and Gregory N. Parsons. “Hydrogen elimination and phase transitions in pulsed-phase plasma desposition of amorphous and microcrystalline silicon.” *Journal of Applied Physics* 81 (1997): 2847-2855.

http://www.nrel.gov/docs/fy99osti/29586.pdf
http://www.nrel.gov/docs/fy05osti/38355.pdf

E. Srinivasan and G.N. Parsons, *J. Appl. Phys.* **81** (1997) 2847

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Commercialization of a-Si / μ-Si

Applied Materials SunFab: Turnkey production lines.

Images removed due to copyright restrictions. Please see

http://www.pv-tech.org/images/uploads/sunfab.jpg

http://www.appliedmaterials.com/products/solar_multimedia_3.html?menuID=9_5

Movie at:

http://www.appliedmaterials.com/products/solar_multimedia_3.html?menuID=9_5

http://www.pv-tech.org/images/uploads/sunfab.jpg

Commercialization of a-Si / μ-Si

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http://www.solarserver.de/images/oerlikon_picture_4.jpg
http://www.ovonic.com/images/me_uni-solar_thin-film_pv_300dpi_large.jpg

Oerlikon

Uni-Solar

Heterojunction with Thin Intrinsic layer (HIT) Cells

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http://www.power-technology.com/projects/Serpa/images/7-serpa-solar.gif

http://www.sanyo.co.jp/clean/solar/hit_e/hit.html

Advantages:
- Less surface recombination.
- Higher maximum voltages ($V_{oc} > 710$ mV).
- Efficiency less temperature sensitive.
- High efficiencies (21.5% on 100 cm^2 cell)

Challenges:
- Deposition: doping, nano-to-micro-crystalline phase transition
- Optimizing the c-Si and a-Si interface, low-damage plasma.

Energy Band Diagram of HIT Cell

Images removed due to copyright restrictions. Please see Fig. 1 and 5 in Taguchi, Mikio, et al. "Obtaining a Higher V_{oc} in HIT Cells." *Progress in Photovoltaics: Research and Applications* 13 (2005): 481-488.

M. Taguchi et al., *Prog. Photovolt: Res. Appl*. **13** (2005) 481.

Temperature Dependence of HIT Cells

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M. Taguchi et al., *Prog. Photovolt: Res. Appl*. **13** (2005) 481.

CIS and its variants

Basic Facts:

- CIS = Copper Indium Diselenide = $CuInSe_2$ = Chalcopyrite
- Zincblende-like structure
- Record efficiencies: 19.2% lab; 13.4% large area

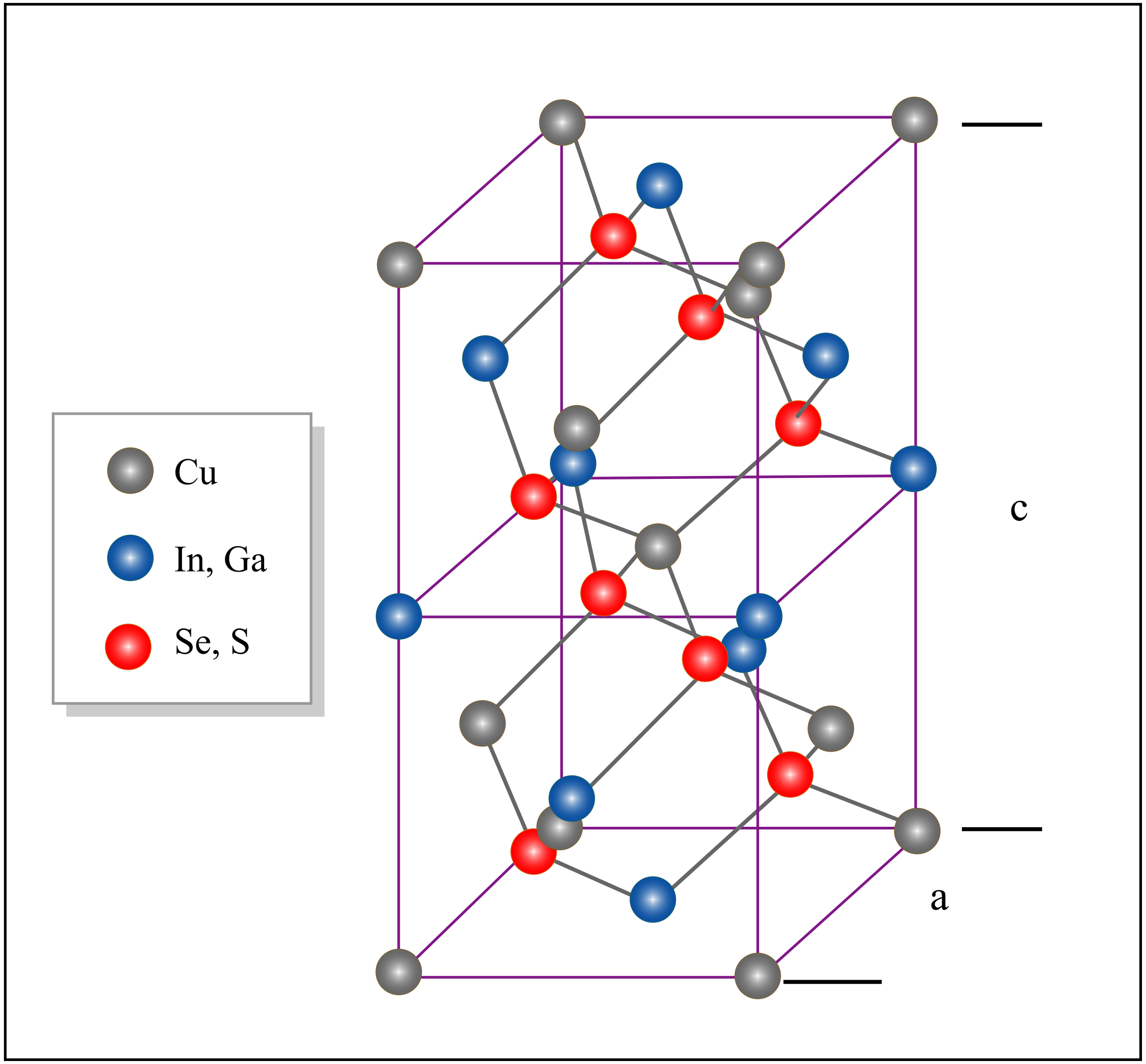

Figure by MIT OpenCourseWare.

Thin-film polycrystalline CIGS

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http://level2.phys.strath.ac.uk/SolarEnergy/img/intro.gif

http://level2.phys.strath.ac.uk

Image removed due to copyright restrictions. Please see Fig. 1 in
Klein, A., et al. “Interfaces in Thin Film Solar Cells.” *Record of the*
31st IEEE Photovoltaic Specialists Conference (2005): 205-210.

A. Klein, *Proc. 31st IEEE PVSC*
(Lake Buena Vista, FL, 2005) p.205

CIS Band Structure Debated

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A. Klein, *Proc. 31st IEEE PVSC*
(Lake Buena Vista, FL, 2005) p.205

Image removed due to copyright restrictions. Please see Fig. 3 in Weinhardt, L., et al. “Band alignment at the *i*-ZnO/CdS interface in Cu(In,Ga)(S,Se)$_2$ thin-film solar cells.” *Applied Physics Letters* 84 (2004): 3175-3177.

L. Weinhardt, C. Heske et al.,
Appl. Phys. Lett. **84** (2004) 3175

CIGS Characteristics

Advantages:
- High efficiencies (~20%)

Challenges:
- Uniform deposition (stoichiometry & thickness) over large areas, quickly
- Defects, Interface States are complex, poorly understood.
- Replacing n-type emitter with Cd-free material.

CIGS Commercialization

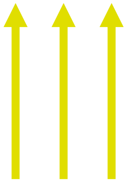
Images removed due to copyright restrictions. Please see
http://www.nanosolar.com/media/firstpanelsshipped_web.jpg
http://imgs.sfgate.com/c/pictures/2005/07/11/bu_solarcell8865.jpg

Start-ups: Nanosolar (above),
Heliovolt, Miasolé…

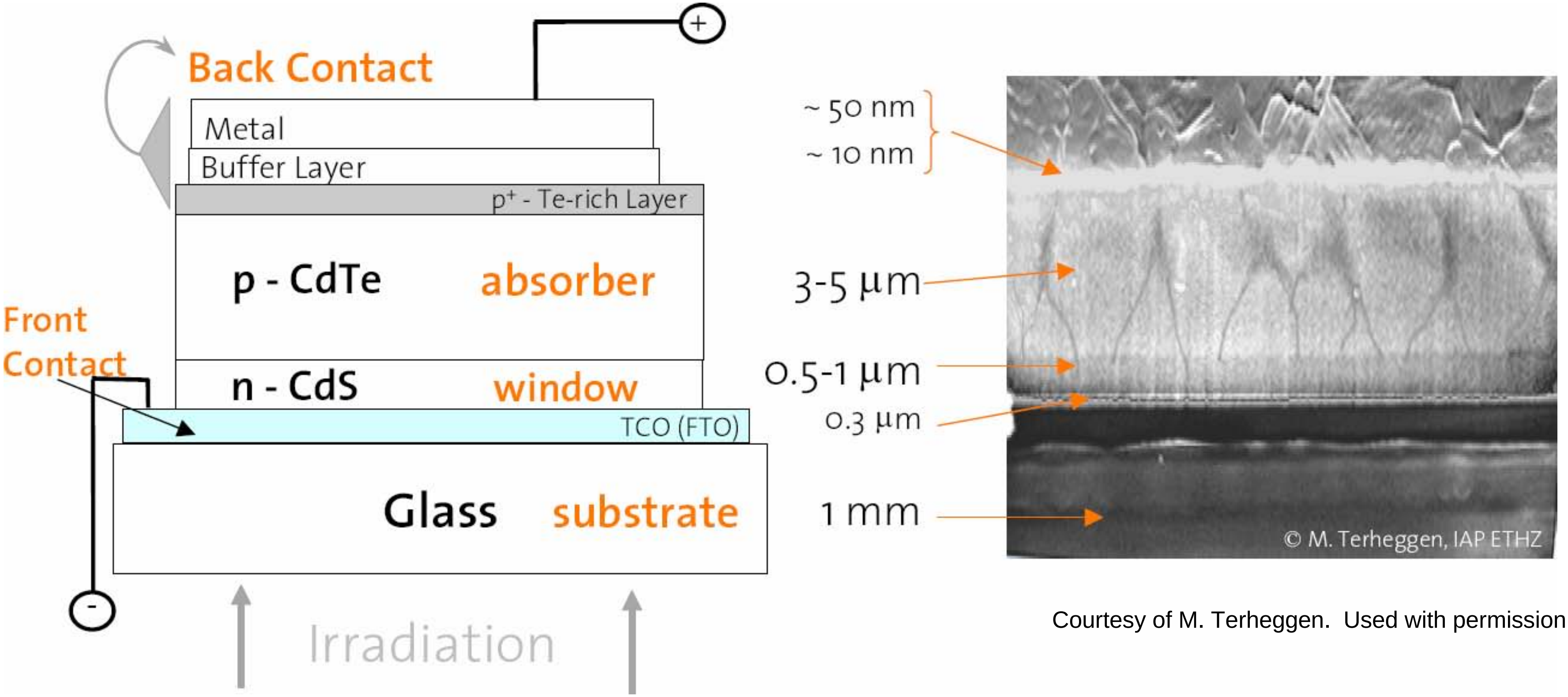
Cadmium Telluride (CdTe)

Image removed due to copyright restrictions. Please see Fig. 1 in Klein, A., et al. “Interfaces in Thin Film Solar Cells.” *Record of the 31st IEEE Photovoltaic Specialists Conference* (2005): 205-210.

A. Klein, *Proc. 31st IEEE PVSC*
(Lake Buena Vista, FL, 2005) p.205



Cadmium Telluride (CdTe)



Courtesy of M. Terheggen. Used with permission.

CdTe

Image removed due to copyright restrictions. Please see Fig. 6 in Klein, A., et al. "Interfaces in Thin Film Solar Cells." *Record of the 31st IEEE Photovoltaic Specialists Conference* (2005): 205-210.

A. Klein, *Proc. 31st IEEE PVSC*
(Lake Buena Vista, FL, 2005) p.205

CdTe Characteristics

Advantages:

- Technology developed for application on glass → BIPV.
- Radiation hardness.

Challenges:

- Cadmium
- Marketability (Greenpeace opposed, banned in Japan)

Environmental Concerns: Cadmium

Arguments Against:

- Suspected carcinogen.
- Industrial emissions tightly regulated, esp. in E.U.
    - Cradle-to-grave requirement.

Arguments in Favor:

- By-product of Zn, Cu mining [1].
    - "Better to tie it up in CdTe than dump it in the ground."
- "Negligible" Cd released during fires [2].
- "Public fear a perception issue" [3].
- CdTe is a stable compound.
    - Much less Cd released per kWh than a battery [4].
- Safe production.
- Full recycling guaranteed (by law in Europe).

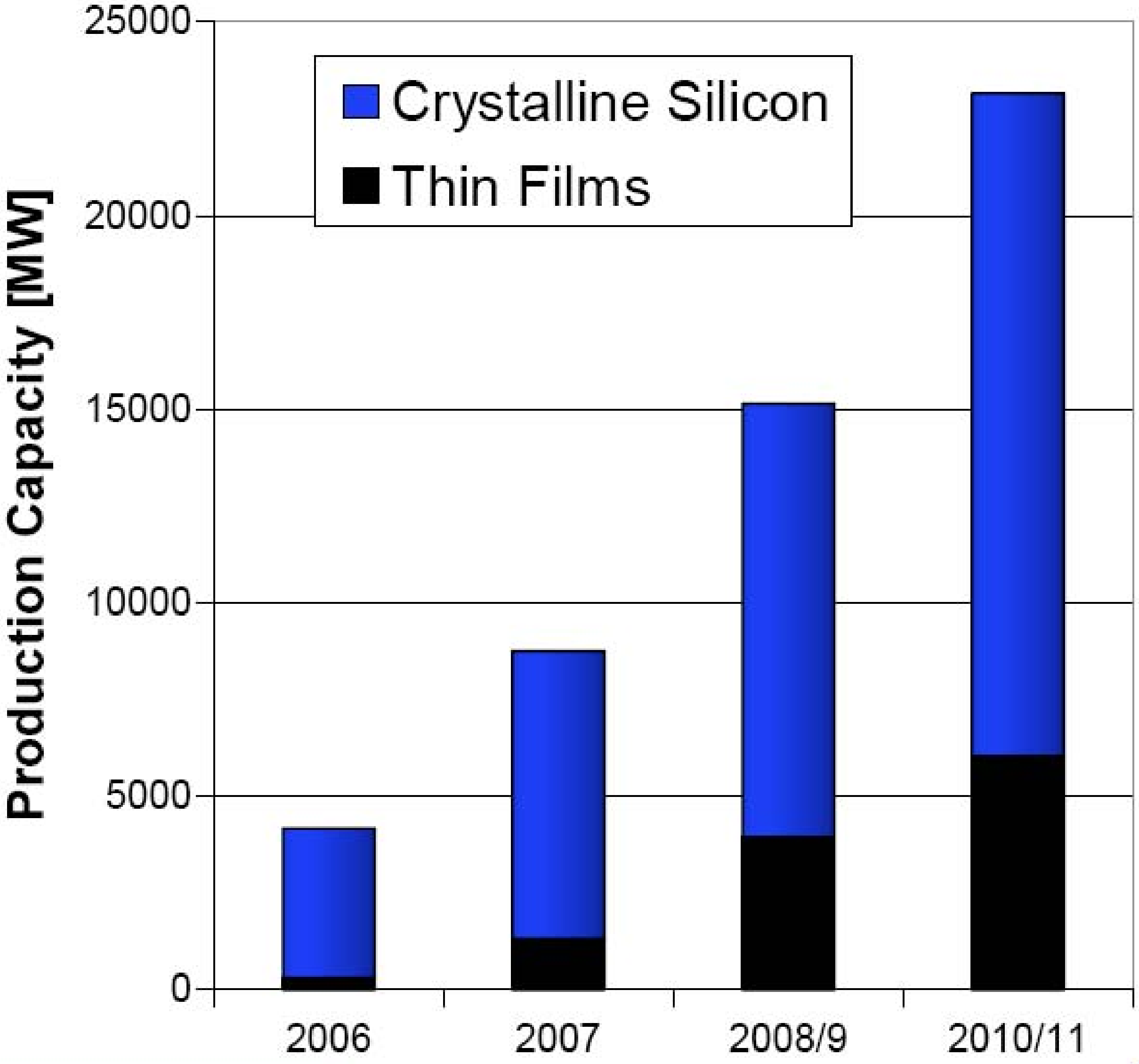
[1] http://www.firstsolar.com
[2] V.M. Fthenakis et al., *Proc. 19th EU-PVSEC* (Paris, France, 2004); Paper 5BV.1.32
[3] http://www.nrel.gov/cdte
[4] V.M. Fthenakis, *Renewable and Sustainable Energy Reviews* **8** (2004) 303.

CdTe Commercialization

Images removed due to copyright restrictions. Please see
http://www.firstsolar.com/images/large_pp5.jpg
http://www.firstsolar.com/images/large_pp6.jpg

First Solar: Proven Technology!

Announced Capacity Increases

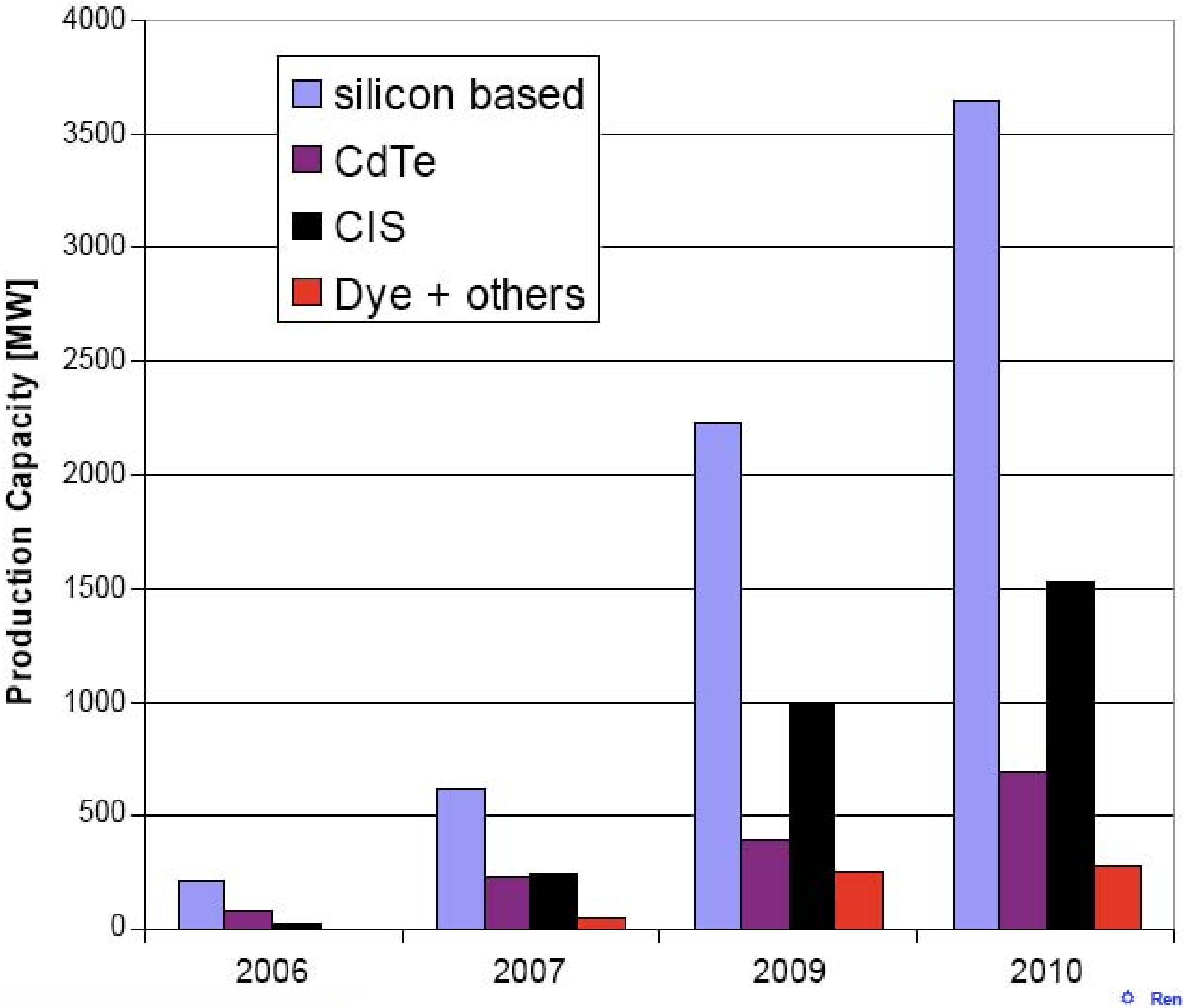


Renewable Energies

ies

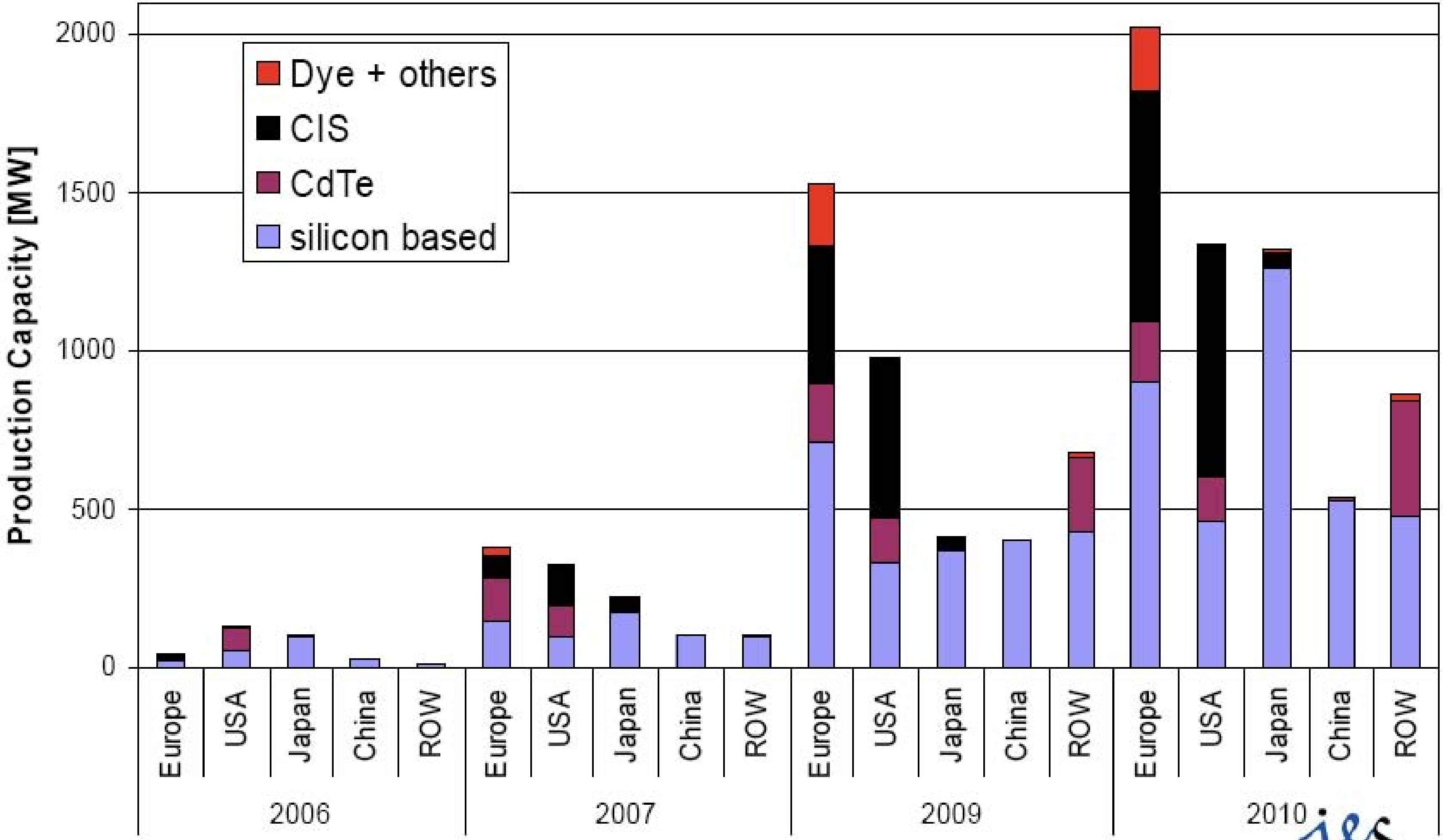
Courtesy Arnulf Jäger-Waldau. Used with permission.

Announced Production Capacities by Technology



Courtesy Arnulf Jäger-Waldau. Used with permission.

Announced Capacity Increases: Regional Differentiation by Technologies



Renewable Energies

ies

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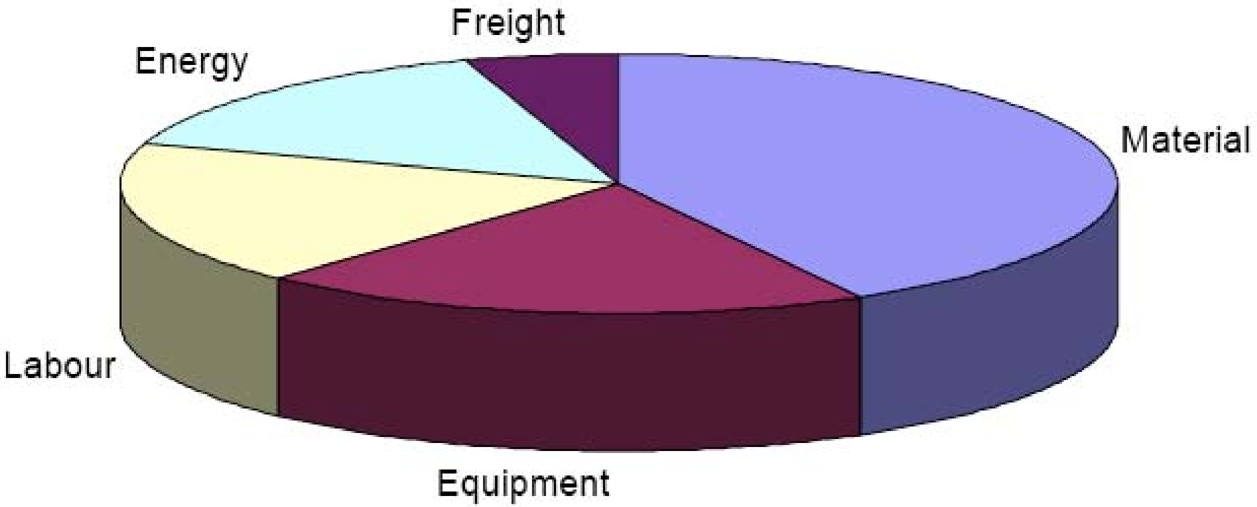
Average Thin Film Cost Structure



Technology dependent Drivers

Deposition Process: Dominates Energy
Deposition Materials: Dominates Depreciation
Package/Assembly: Dominates Materials

Common Drivers

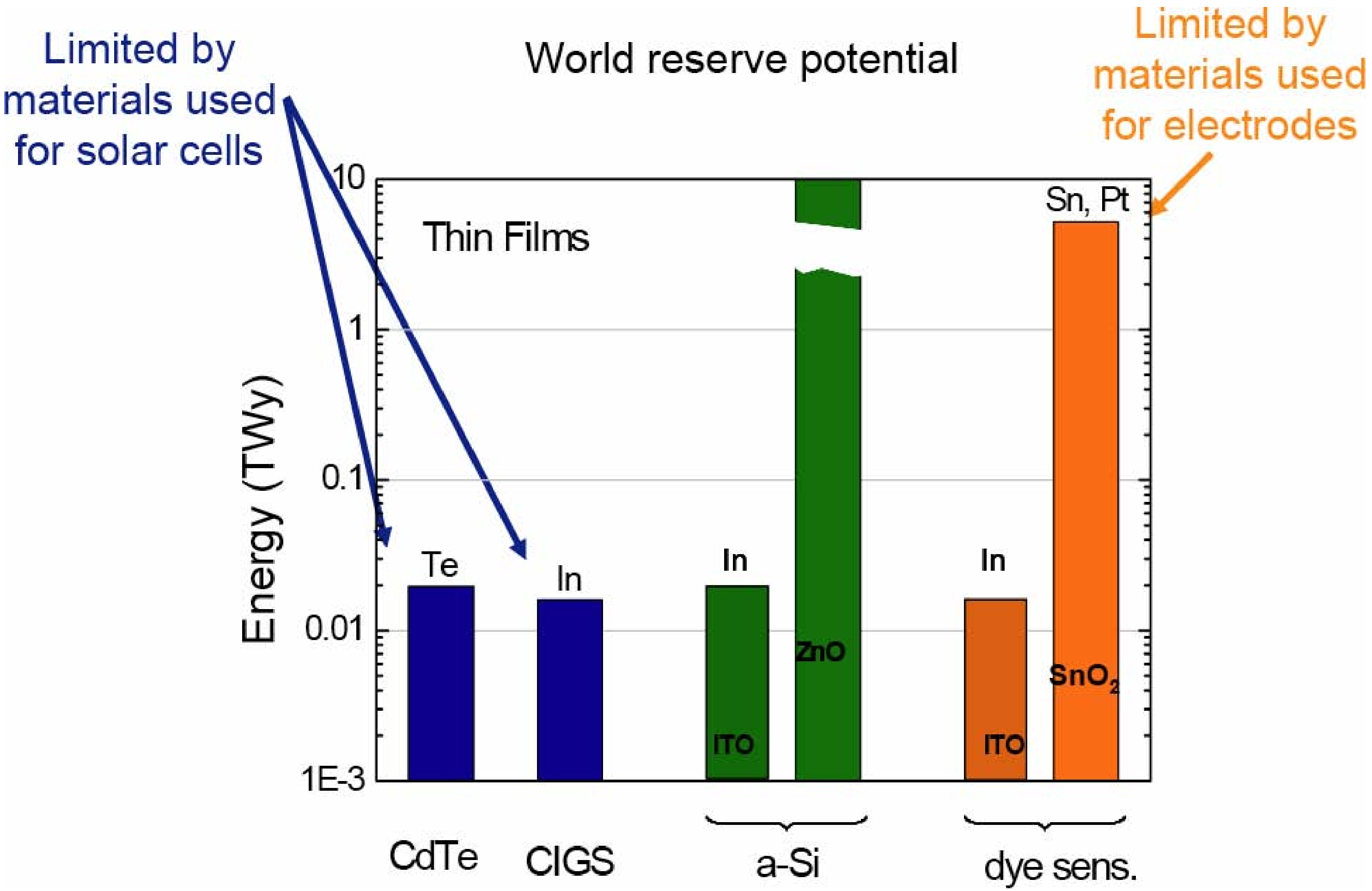
Material Cost: Volume, Efficiency
Depreciation: Throughput, Efficiency
Labour: Throughput, Automation, Efficiency
Energy: Throughput, Efficiency

Courtesy Arnulf Jäger-Waldau. Used with permission.

Materials Availability

Most experts agree: not enough In, Te to produce TW of PV.

Development of new TCO materials may reduce costs.



Source: Feltrin, A., A. Freundlich. “Material Considerations for Terawatt. Level Deployment of Photovoltaics.” *Renewable Energy* 33 (2008): 180-185. Courtesy of Alex Freundlich. Used with permission.

Alex Freundlich: http://www.rio6.com/proceedings/RIO6_181106_MA_1730_Freundlich.pdf

Tandem (Heterostructure) Cells

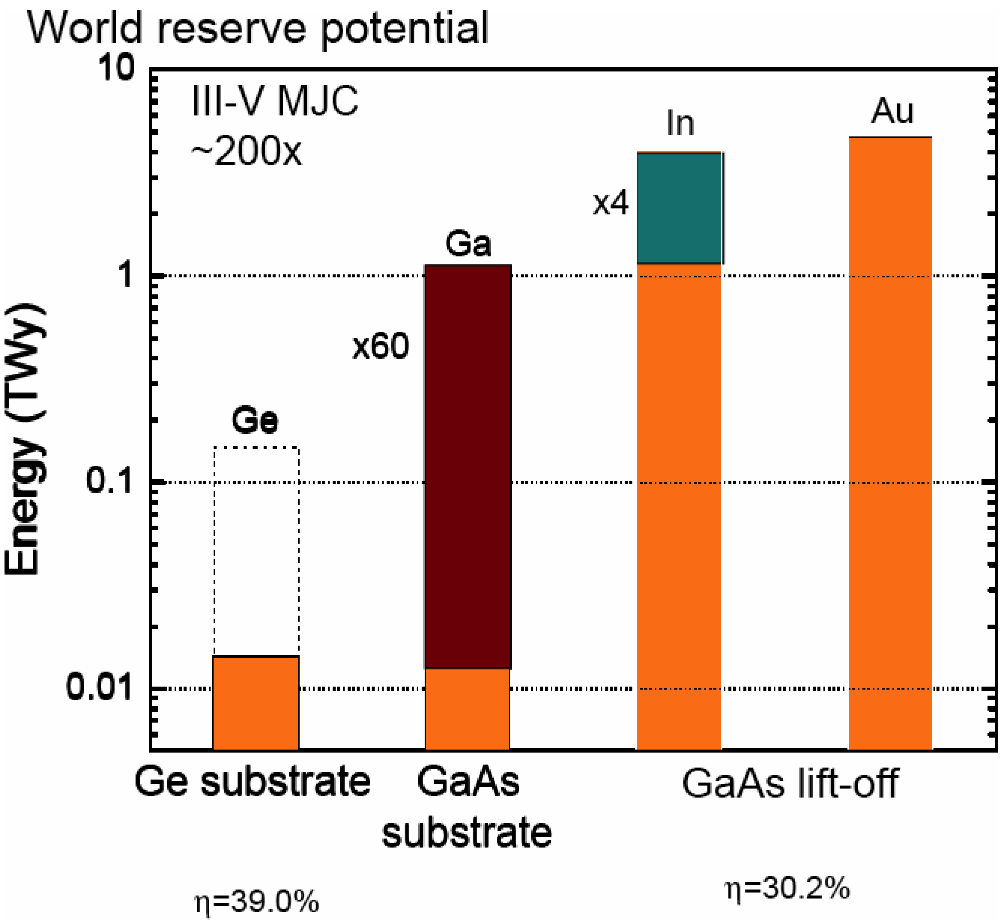
Images removed due to copyright restrictions. Please see
http://www.spectrolab.com/DataSheets/TNJCell/utj3.pdf

- Stack of lattice-matched materials with decreasing bandgaps.
- Spectrolab Cells: $GaInP_2$/GaAs/Ge. Eff_{max}=32%, Eff_{ave}=28%. 375 kW in orbit!
- Theoretical efficiency limit for infinite tandem cell: 86.8%
- *Heteroepitaxial growth slow and expensive!*

Materials Availability

Most experts agree: not enough Ge to produce TW of PV.

Development of new low-bandgap materials.



Source: Feltrin, A., A. Freundlich. "Material Considerations for Terawatt. Level Deployment of Photovoltaics." *Renewable Energy* 33 (2008): 180-185. Courtesy of Alex Freundlich. Used with permission.

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