National Renewable Energy Laboratory
Innovation for Our Energy Future

The Potential of Photovoltaics

AIMCAL 2008

2008 Fall Conference
Vacuum Web Coating

Brent P. Nelson

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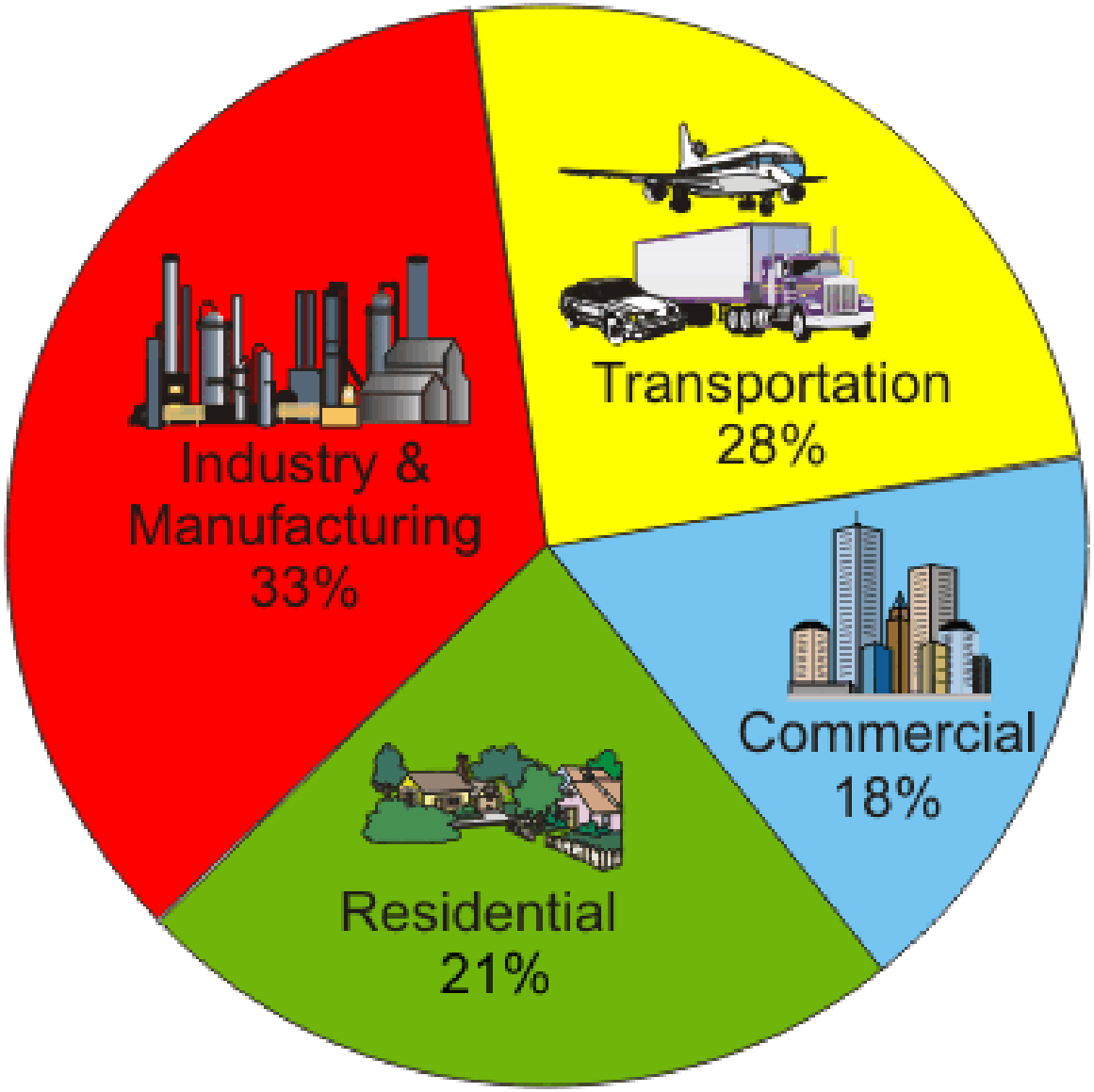
The Potential of PV: Course Outline

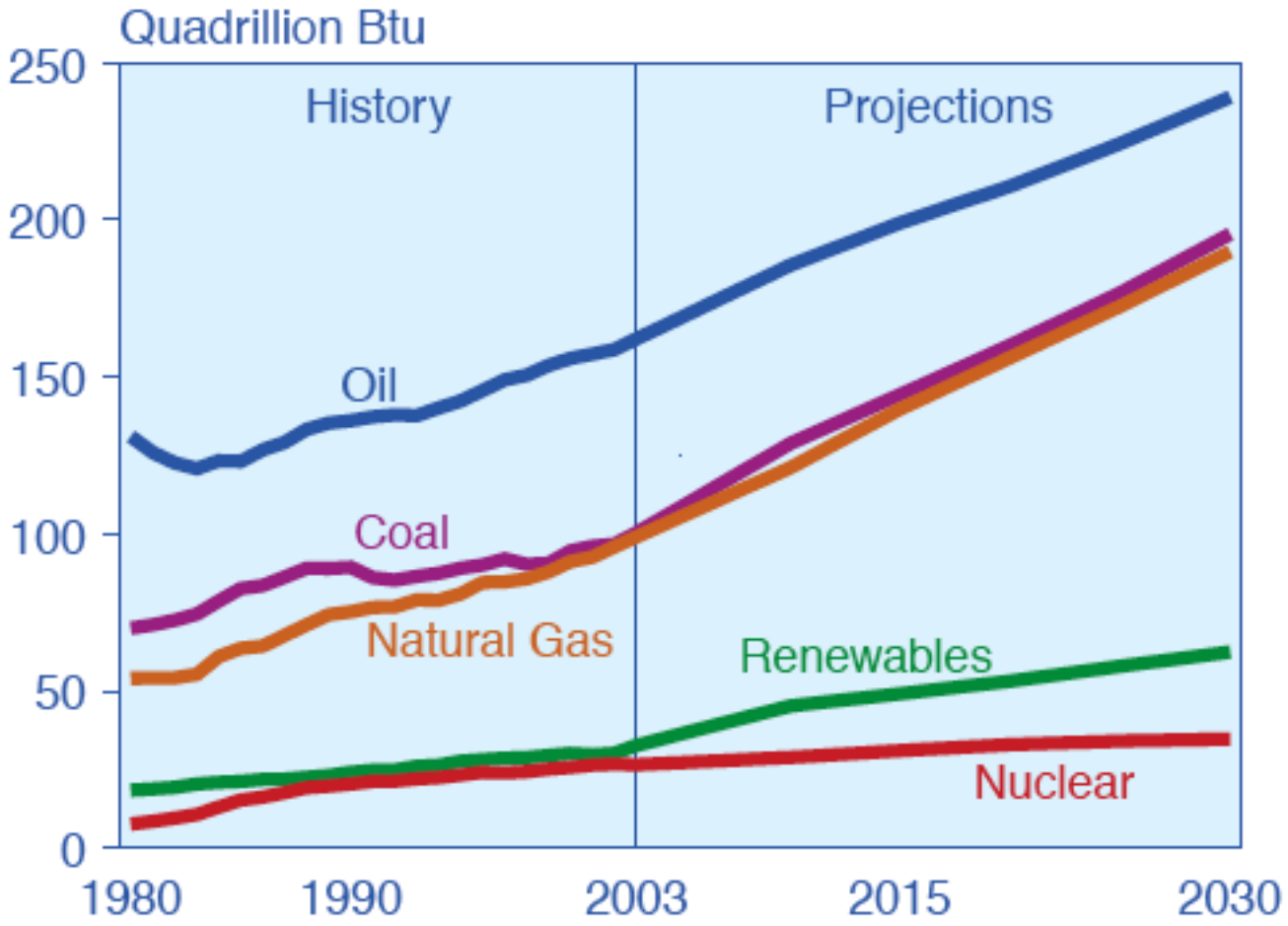
1. The Energy Market
2. Introduction to Photovoltaics (PV)
3. Current PV Technologies
   a) crystalline silicon (c-Si)
   b) amorphous silicon (a-Si:H)
   c) cadmium telluride (CdTe)
   d) copper indium gallium selenide (CIGS)
   e) others, concentrator PV, organic PV, sensitized cells, etc.
4. Technology Comparison
5. PV Technology Trajectory

Breakdown of US Energy Use

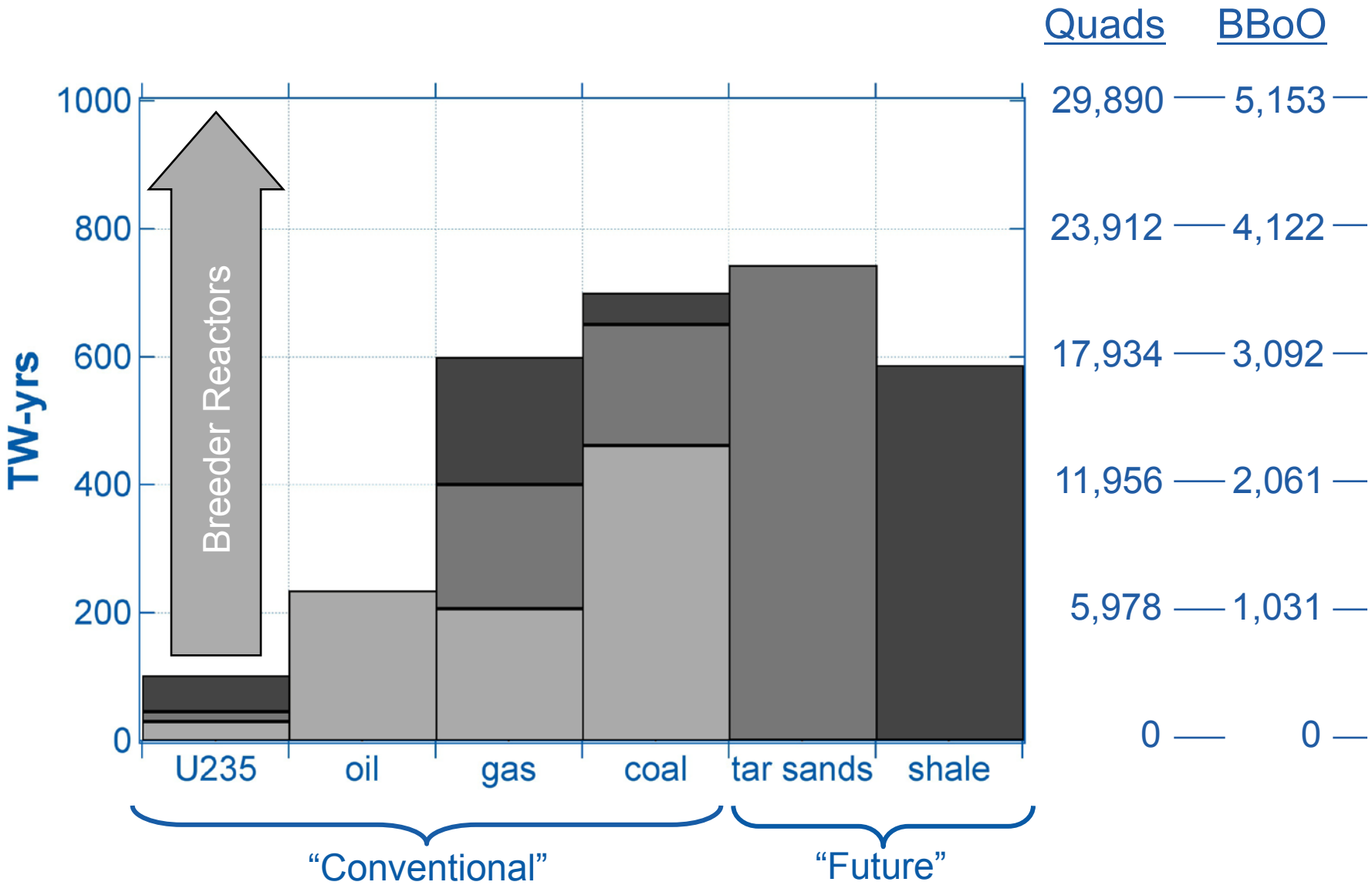


We use Mostly Chemical Energy

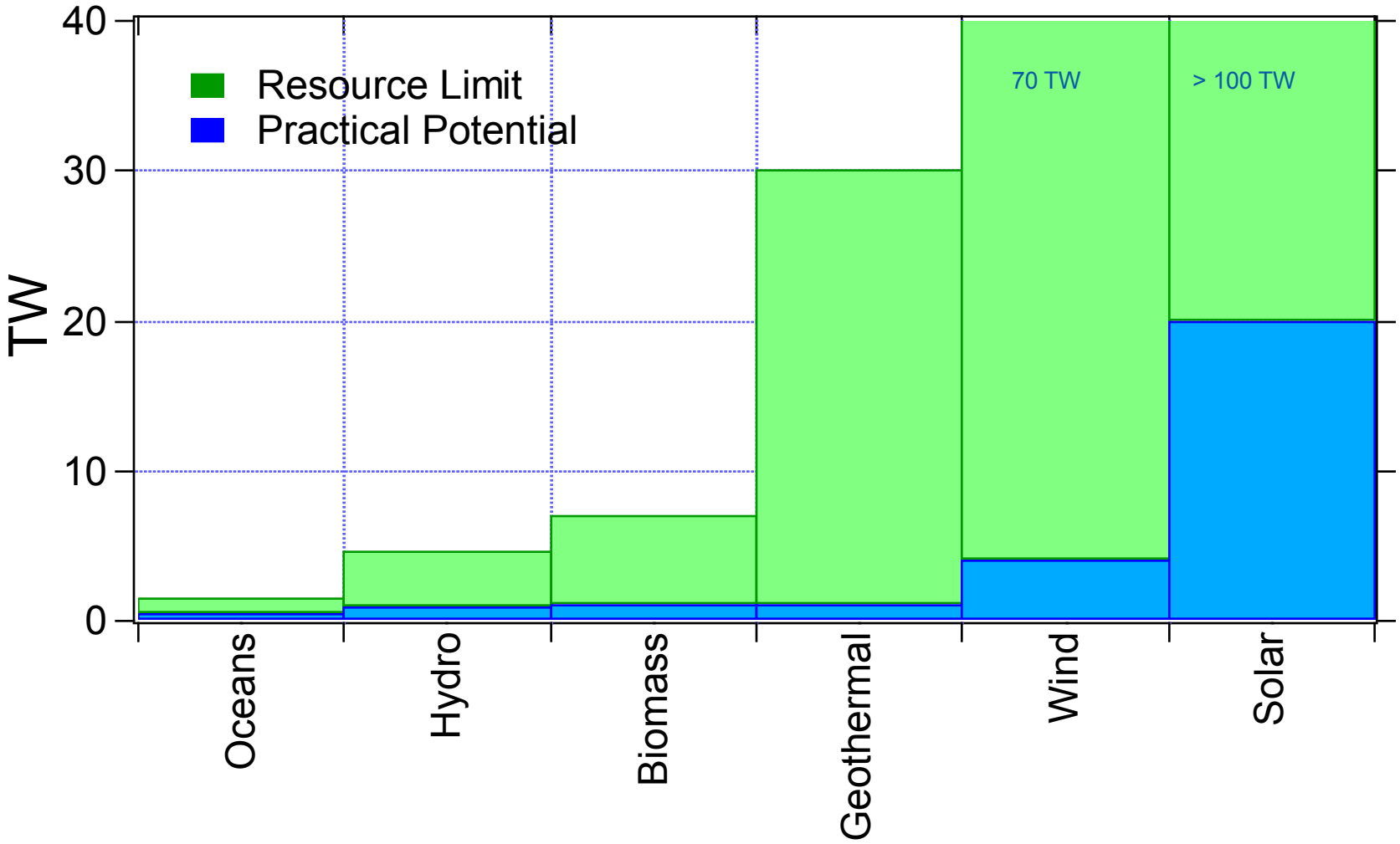
Figure 3. World Marketed Energy Use by Energy Type, 1980-2030



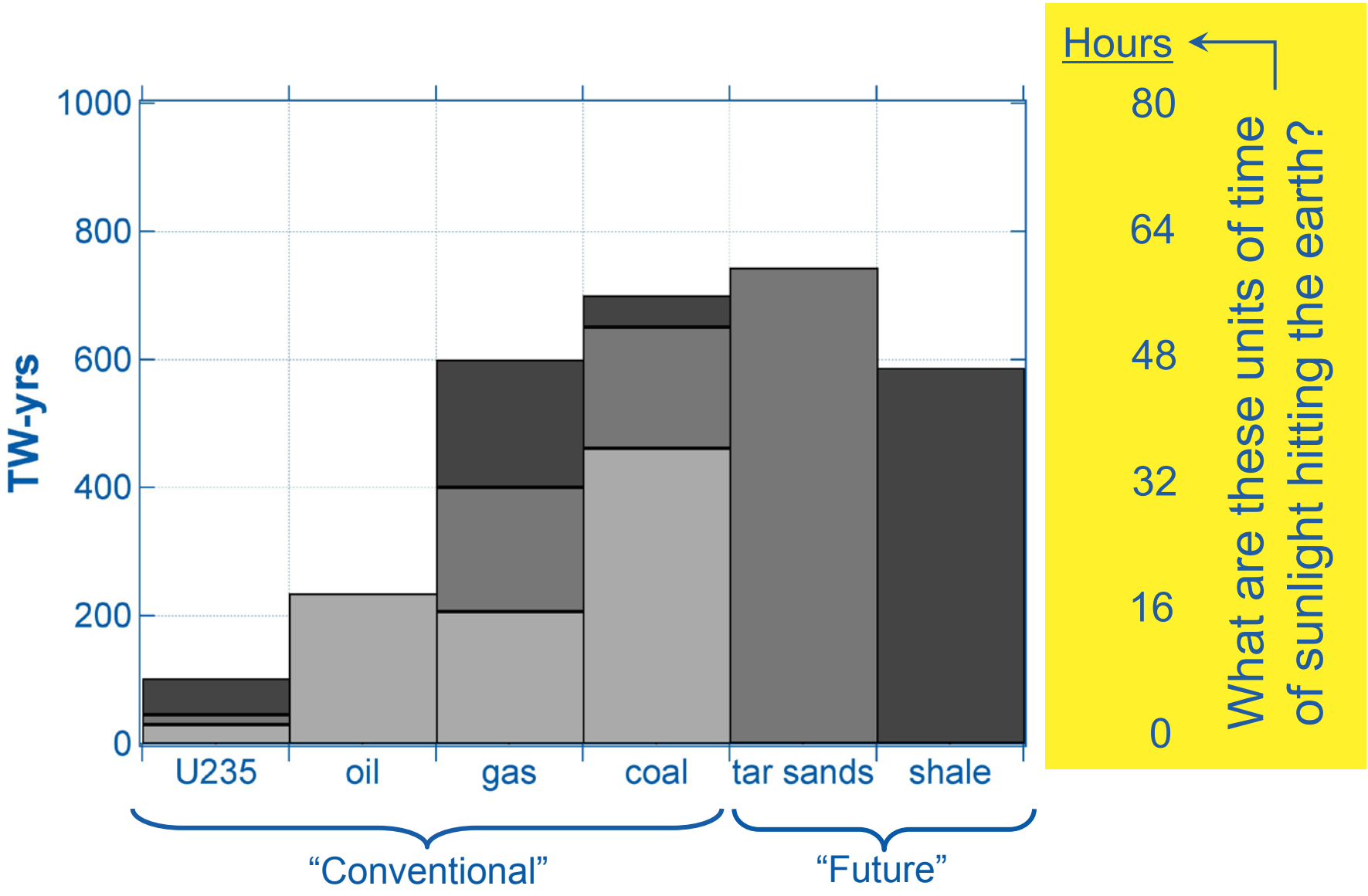
World's Consumable Resources



Sustainable Resource Potential



Consumable Resources



Solar Energy Technologies

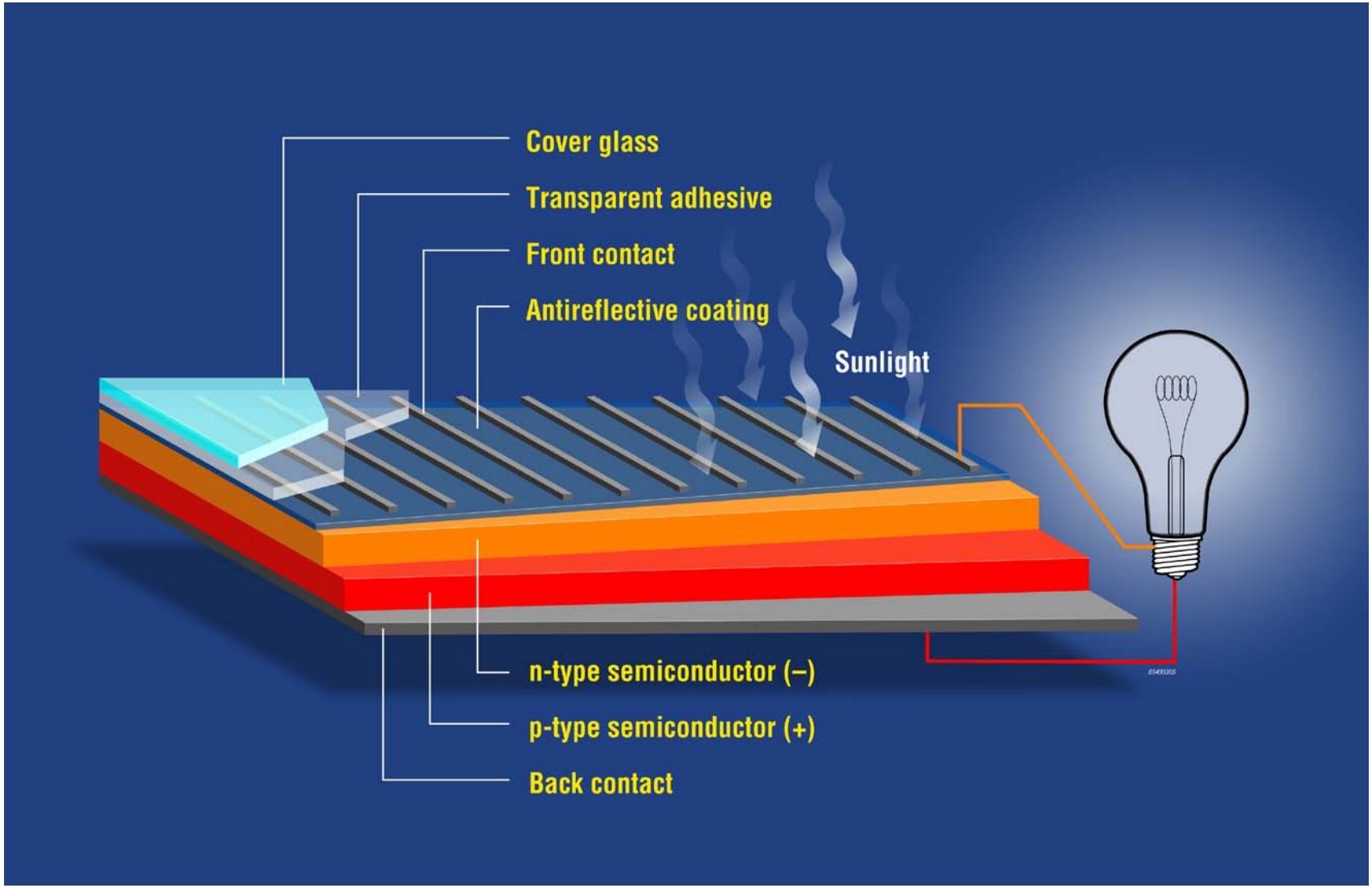
Concentrating Solar Power

Passive Solar (space heating)

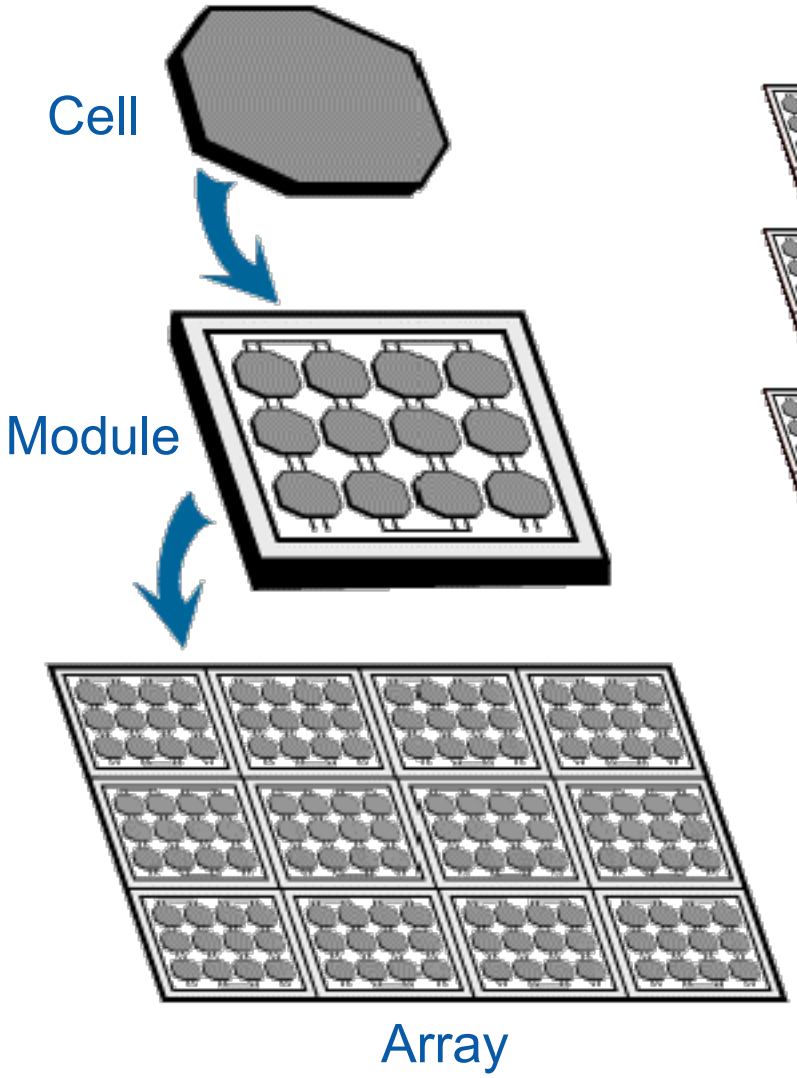
Solar Hot Water

Solar Electric - Photovoltaics

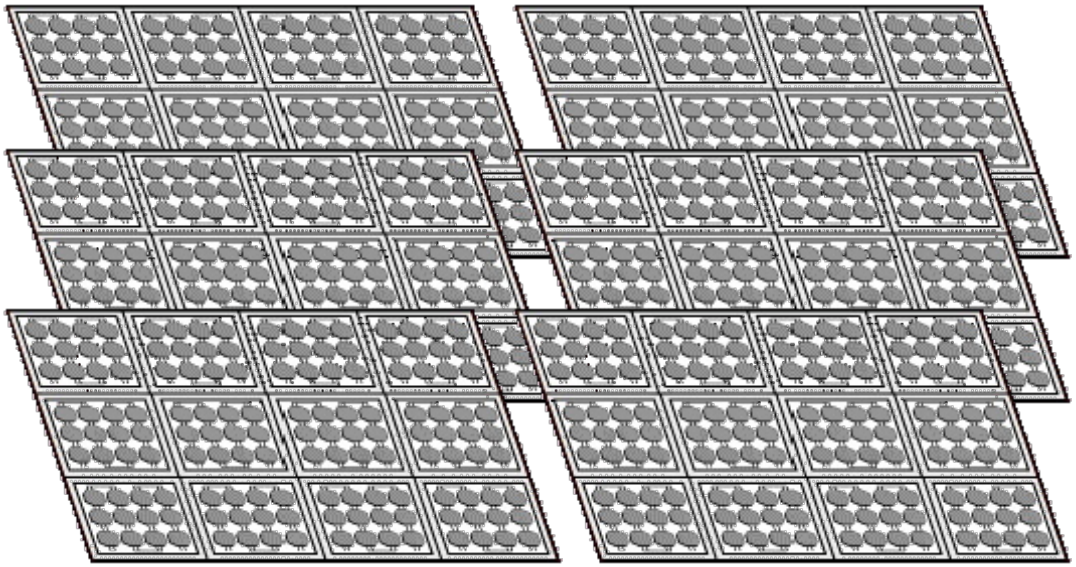
The Basic Solar Cell



PV Systems Building Blocks



System



Includes storage, voltage regulation, inverters, etc.

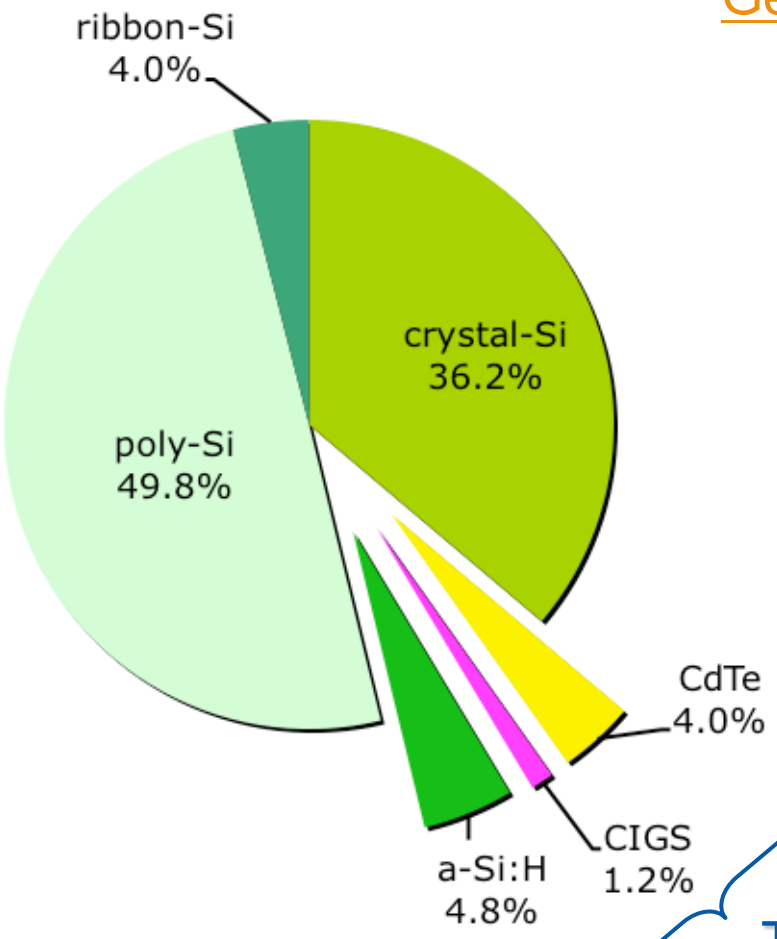
PV Technologies

Generation

Flat plates
- Crystalline silicon — 1
- Thin films — 2
- New technologies — 3

Concentrators
- Silicon — 1
- Multijunctions (III-Vs) — 2

2007 Flat Plate Module Production



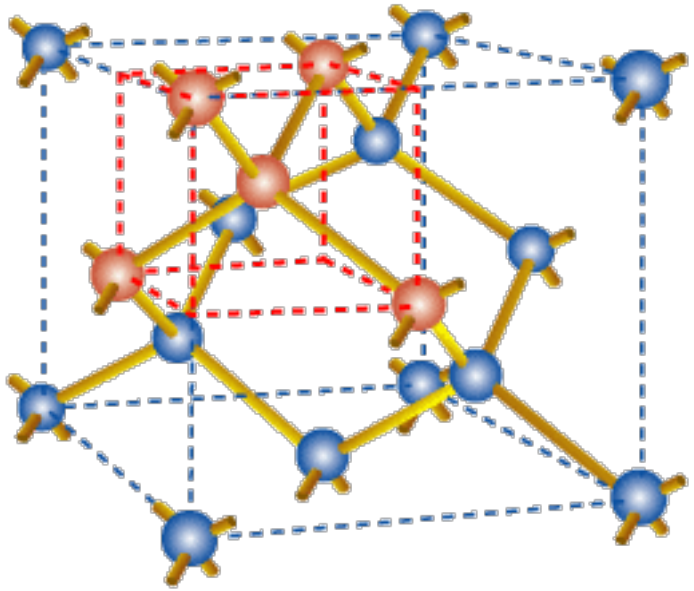
Generation

3,733 MW Total Production

1 • 90% is crystalline silicon

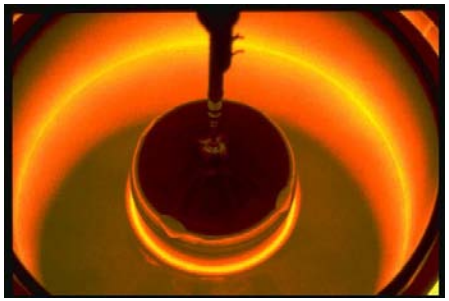
2 • 10% is thin-films (pulled out)

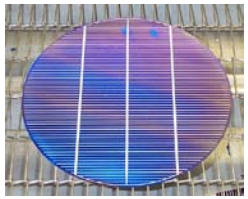
• 95% contains silicon (greens)



Crystalline Silicon = Wafers

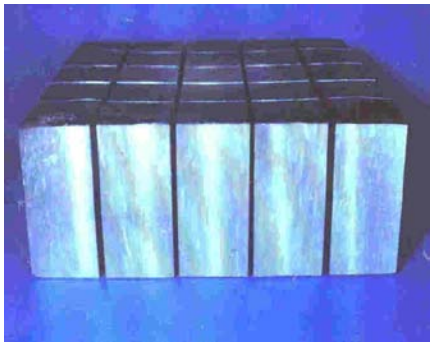
Single Crystal Si

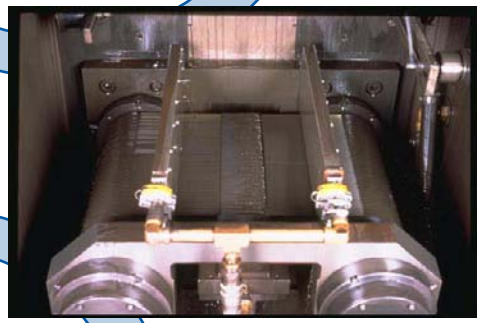




Wafering

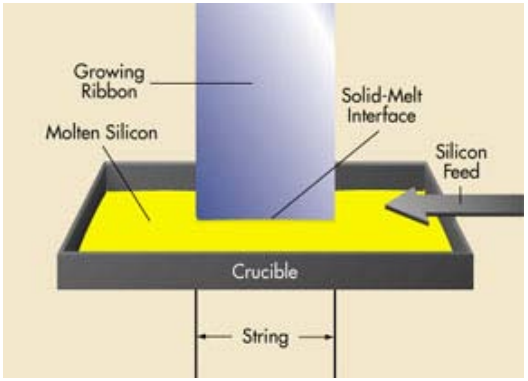
Multicrystalline Si



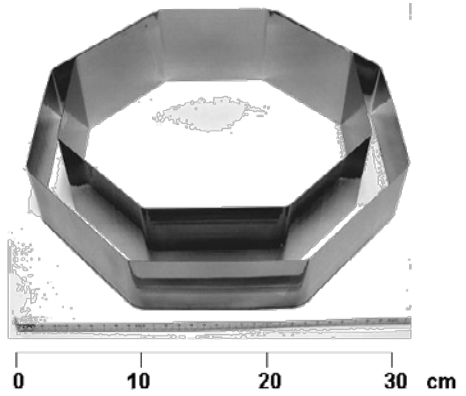


Ribbons ≠ Wafering

String Ribbon Si

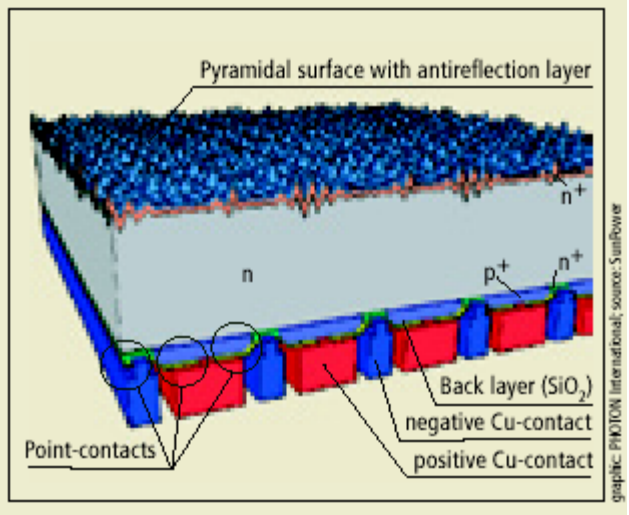


Edge-Defined Film-Fed Growth (EFG) Si



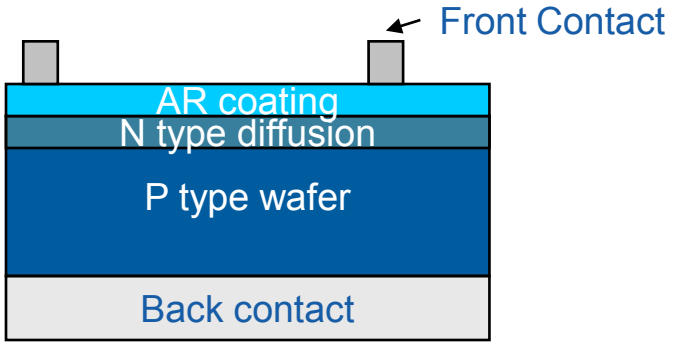
c-Si – Device Structure

Best Commercial Sample Structure

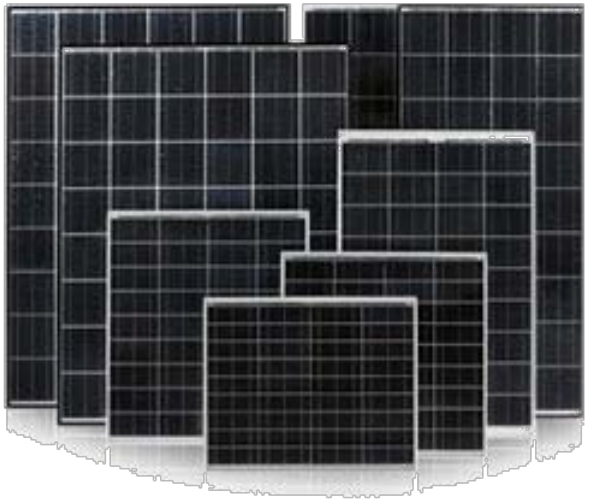


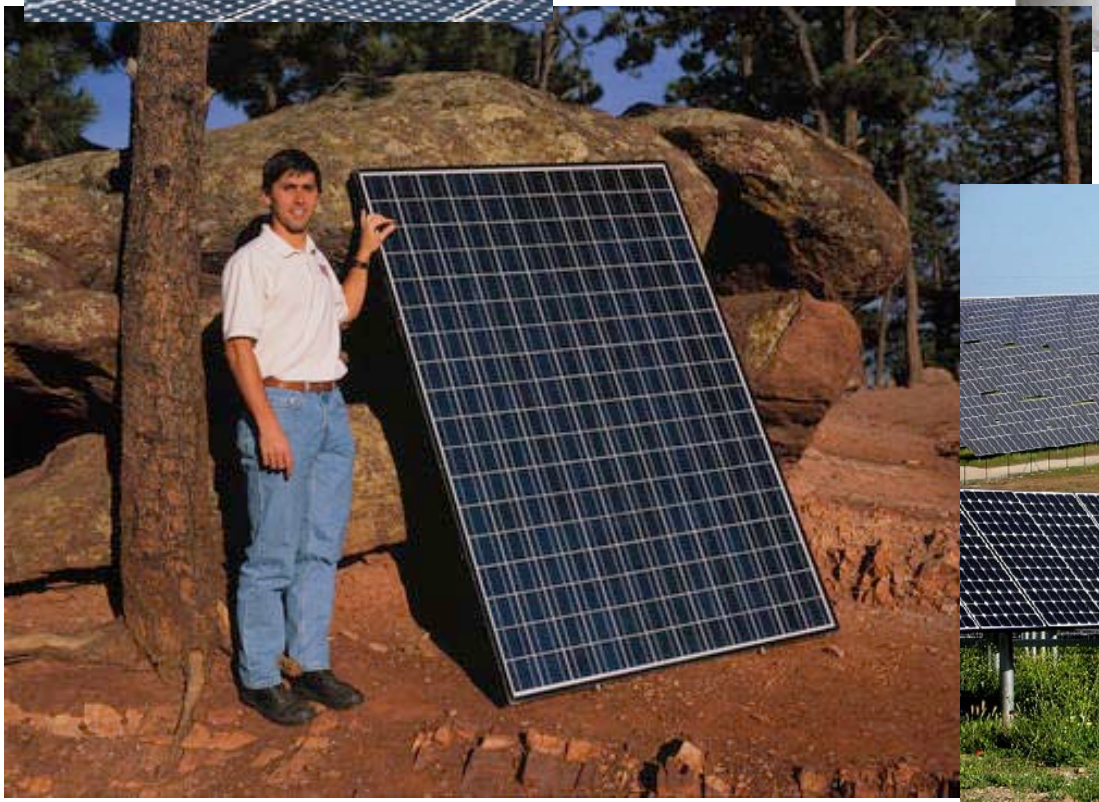
Point-contact cell
SunPower – 21.5%

Common Industrial Cell Structure



C-Si Modules





Crystalline Silicon (c-Si)

Pros

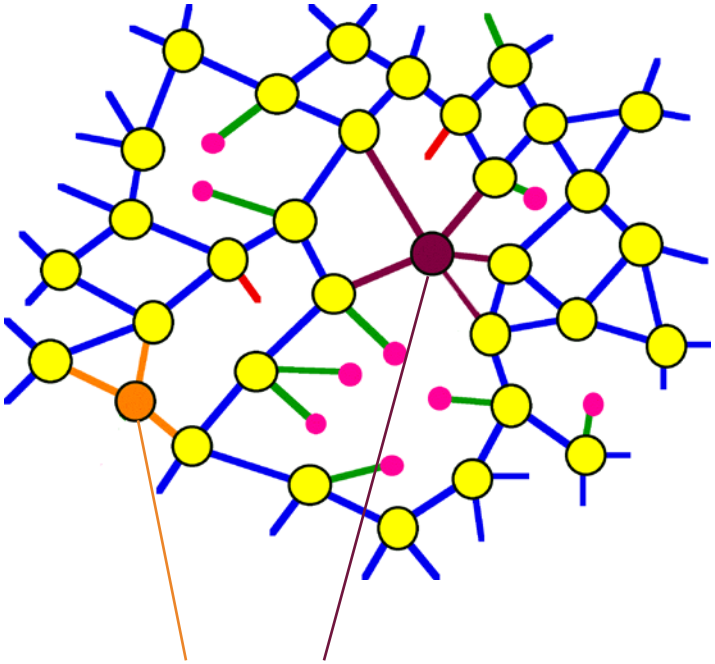
- Well understood material system because of IC industry
- Equipment to production is readily available from multiple vendors.
- Lower barriers to entry for new companies
- Elemental abundance

Cons

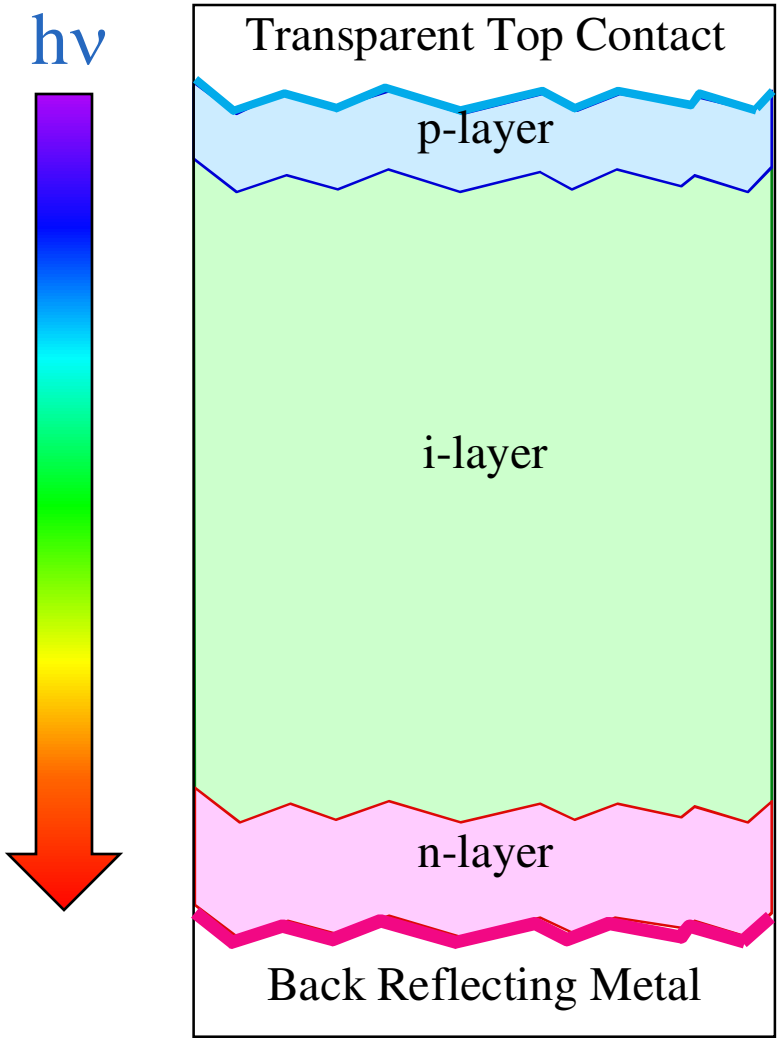
- Si wafers are energy intensive to manufacture
- Feed stock processing growth rate constrains growth
- Actually a family of several device structures, substrates, and production technologies
- Indirect band gap
- Not monolithically processed
- Wafer technology (too thick ~ 200 microns)
- Not many web-coating applications

Amorphous Silicon: Very Thin

a-Si:H

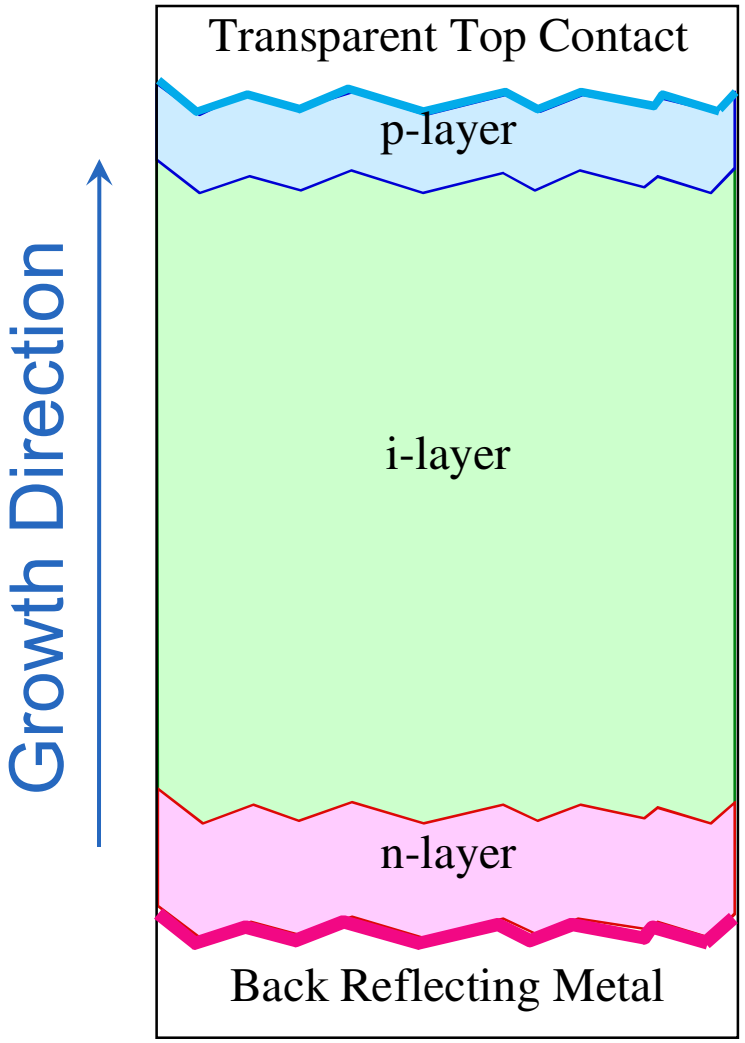


B or P dopants
can be fully satisfied
∴ need %-levels



Typical Growth Techniques

- Encapsulation
- Laser Patterning
- Top Contacts
  - Metal Grids…
    fingers by PVD or wire
  - TCO's… ZnO, ITO by PVD
- Semiconductor Layers
  - CVD techniques
  - PVD in research
- Bottom Contacts
  - Metals… Ag, Al, by PVD
  - Texturing… ZnO by PVD



a-Si:H Modules

Amorphous Silicon (a-Si:H)

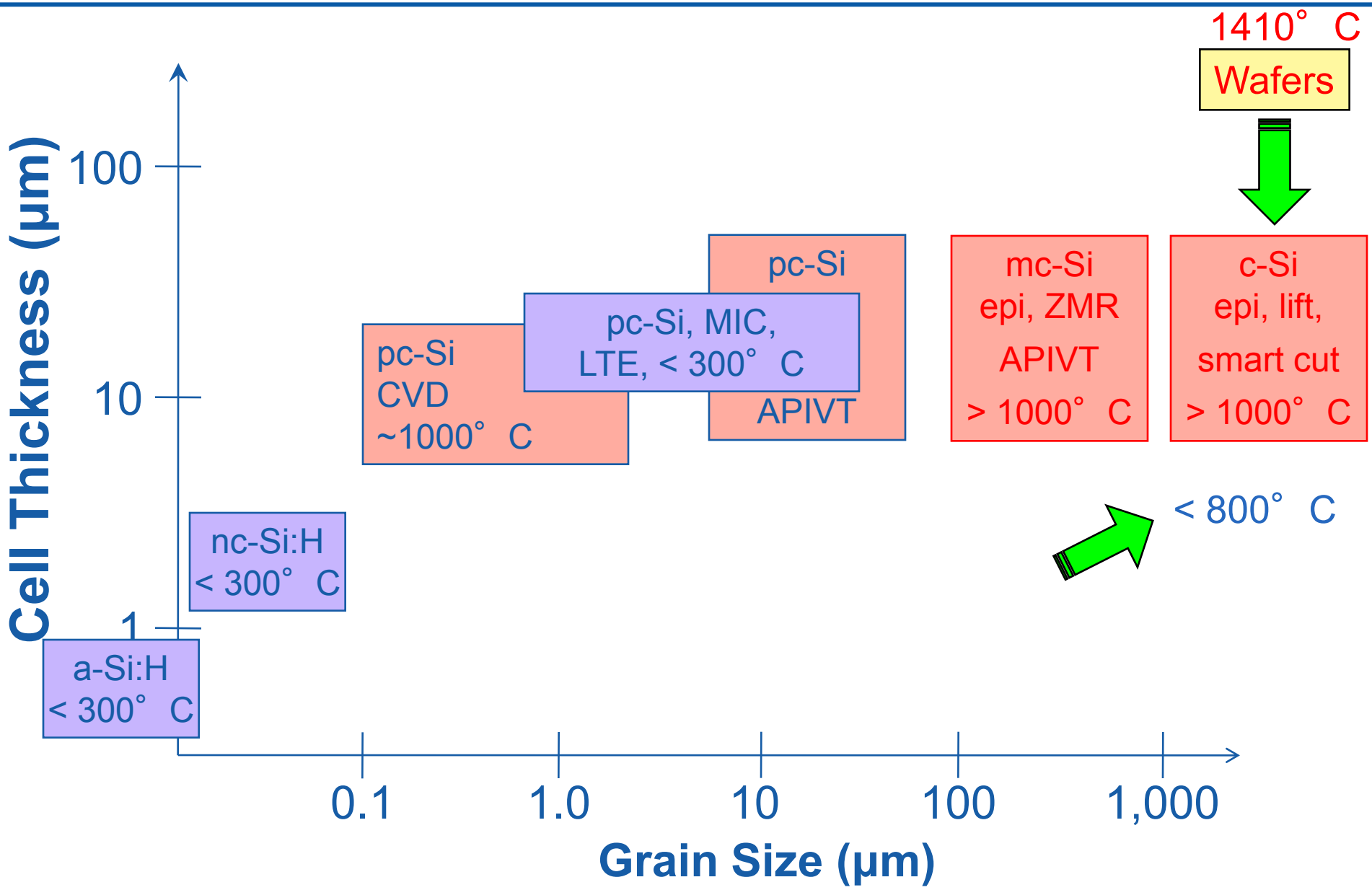
Pros

- Well understood material system – lots of science
- Leverage off TFT industry
- At least three companies selling "turn key manufacturing" facilities
- Elemental abundance
- Scalable manufacturing techniques
- Low temperature processes
- Very thin absorbers
- Many web-coating applications

Cons

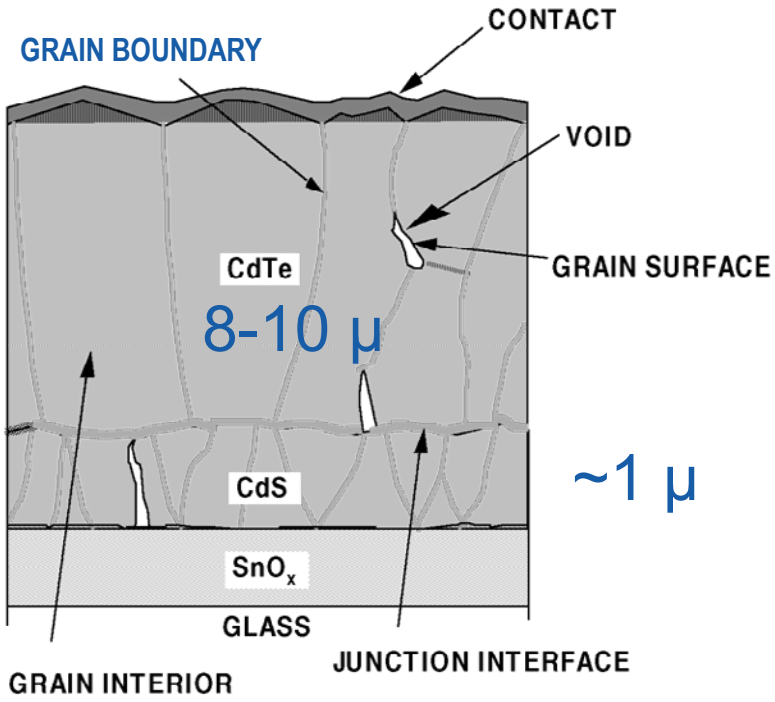
- Doesn't work well in red end of solar spectrum
- Low hole-mobility
- Light induced metastability
- Lowest efficiency of readily available technologies
- Many size "standards"
- Many substrate "standards"

Future of Film-Silicon PV

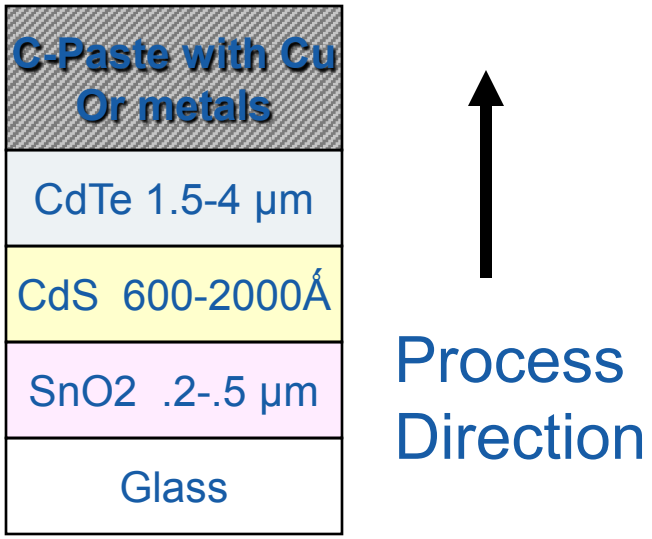


CdTe – Device Structure

Best Laboratory sample structure

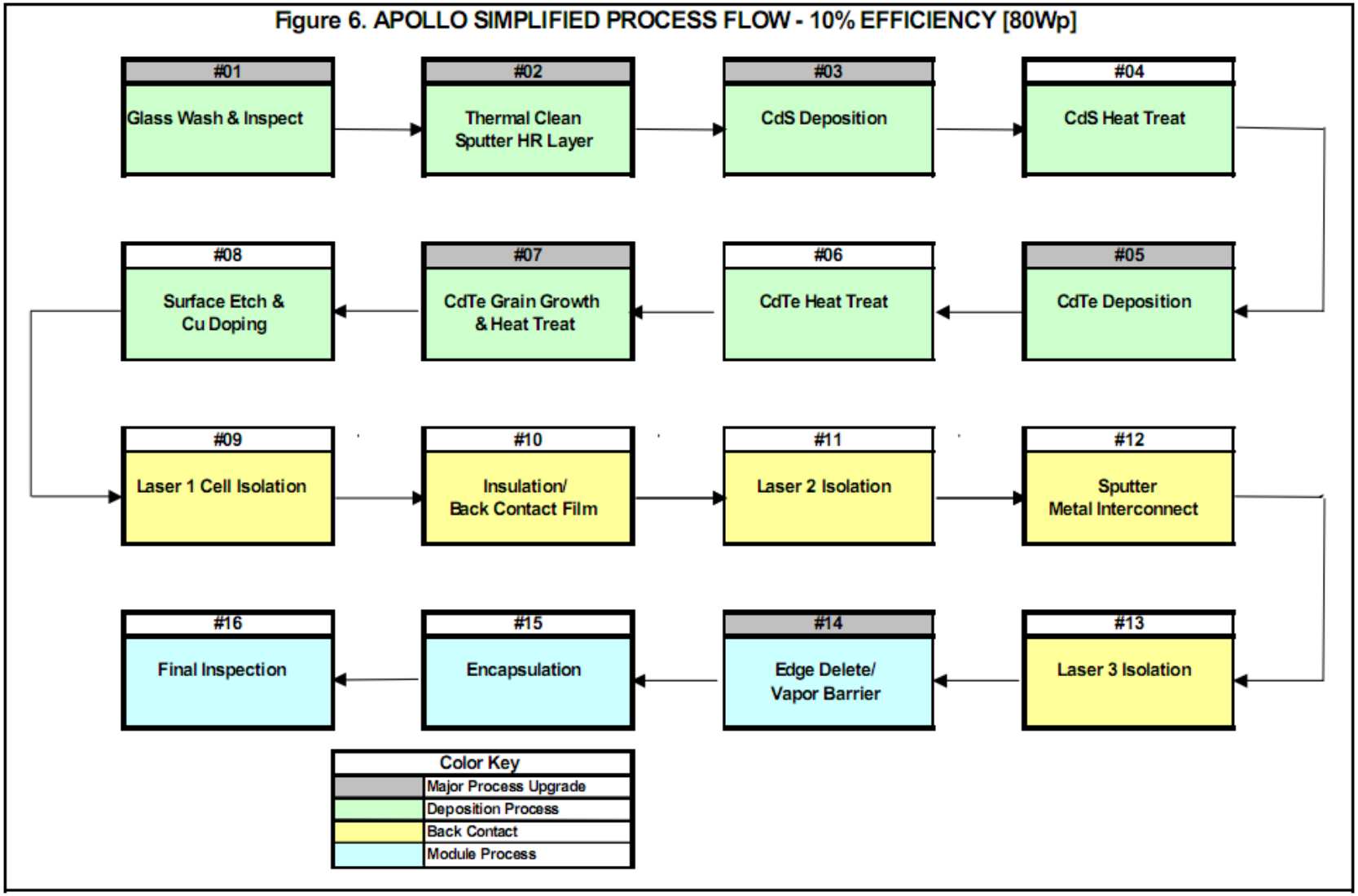


Common Industrial module structure



Ref: Tim Gessert, 3M Tech Forum, 7/19/06

“Typical” CdTe Process



Ref: G. Braun & D. Skinner, Experience Scaling-Up Manufacturing of Emerging Photovolltaic Technologies, NREL SR-640-39165, Jan 2007, p 42

CdTe Modules

CdTe – Thin film

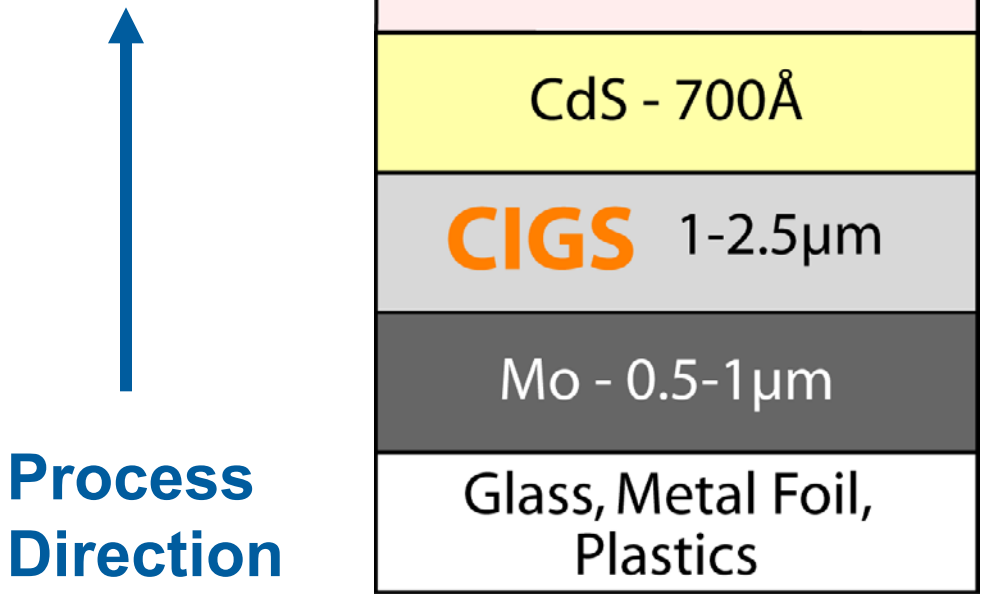
Pros

- Low Manufacturing Cost
- Highest deposition rate of absorber materials = good Manufacturability
- High efficiency laboratory cells = great promise
- Best Laboratory: > 16%
- Champion Modules at 12.5%
- Monolithic Module construction
- Nice Aesthetics
- 2 component manufacturing that is very impurity tolerant

Cons

- Not as well understood as Si materials
- No Industry standard size or fabrication techniques
- No one sells equipment to build these modules.
- Commercial Modules: 8-10.5
- Cd toxicity issues are know, and CdTe toxicity issues are being debated.
- Not currently many web-coating applications

CIGS – Device Structure



- Zn - Zinc
- O - Oxygen
- Sn - Tin

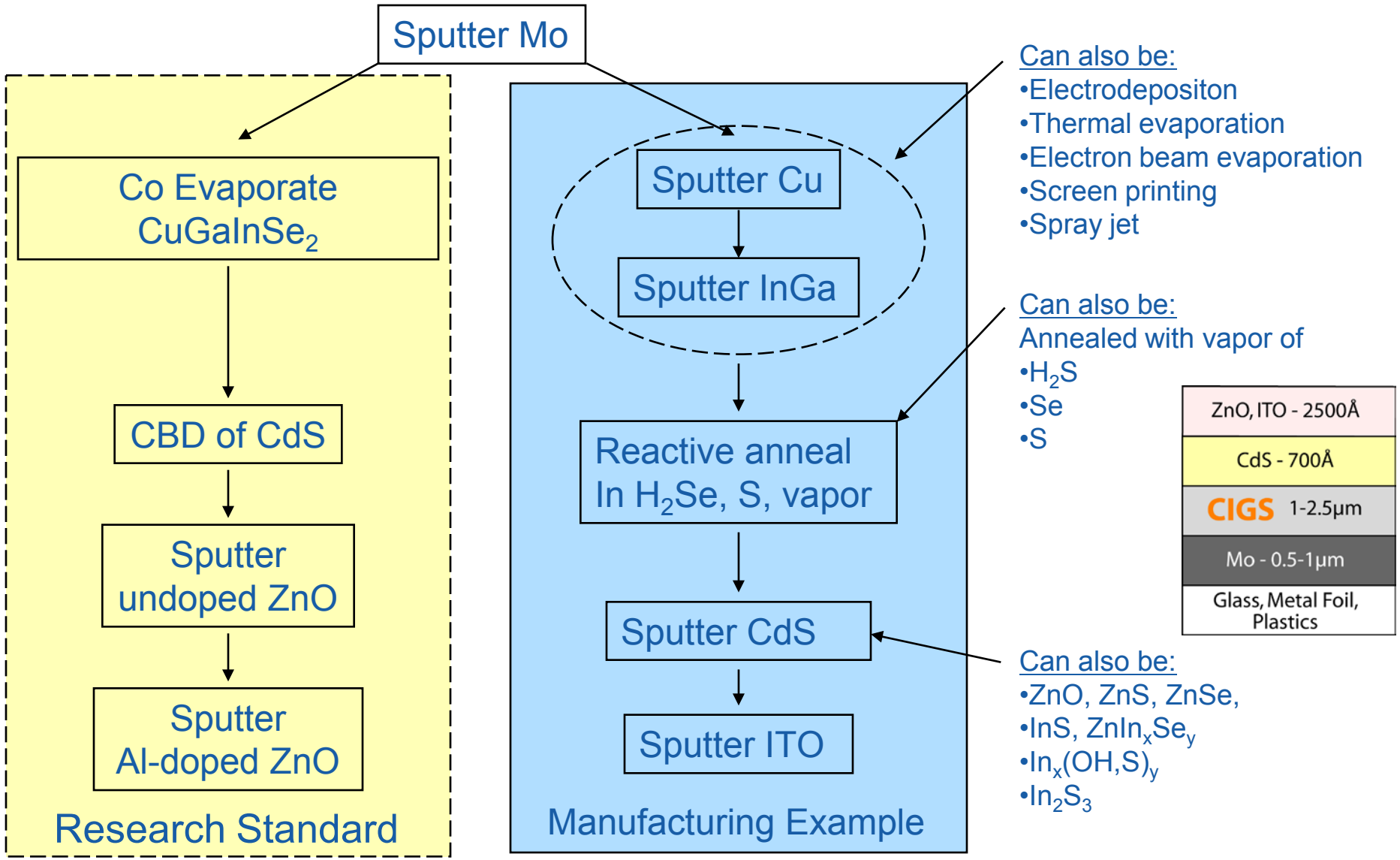
- Cd – Cadmium
- S – Sulphur

- Cu - Copper
- In - Indium
- Ga - Gallium
- Se – Selenium

- Mo - Molybdenum

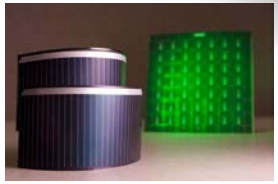
Ref: Tim Gessert, 3M Tech Forum, 7/19/06

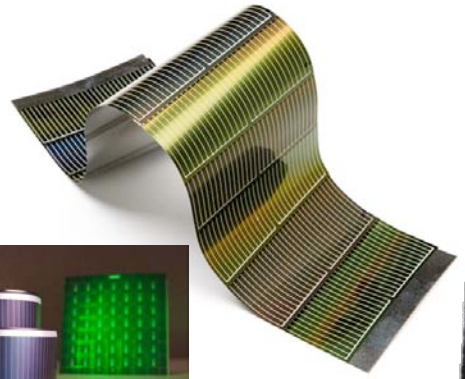
"Typical" CIGS Process



Ref: Handbook of Photovoltaic Science and Engineering, Luque and Hegedus, chapter 13, Shafaman and Stolt, p 583.

CIGS Modules





CIGS – Thin film

Pros

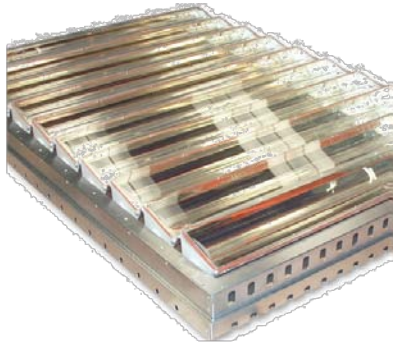
- Possible low manufacturing cost
- Possible high deposition rate of absorber materials
- Highest efficiency laboratory cells = great promise
- Best Laboratory: > 19.9%
- Monolithic Module construction
- Very Nice Aesthetics
- Three “turn-key factory” companies
- Many web-coating applications

Cons

- Requires large area stoichiometry of 4 elements
- High efficiency processes require strict uniformity
- Not as well understood as Si materials
- No Industry standard for size or fabrication techniques
- Best Commercial Modules: 13.4%
- Increasing deposition rates lowers efficiency

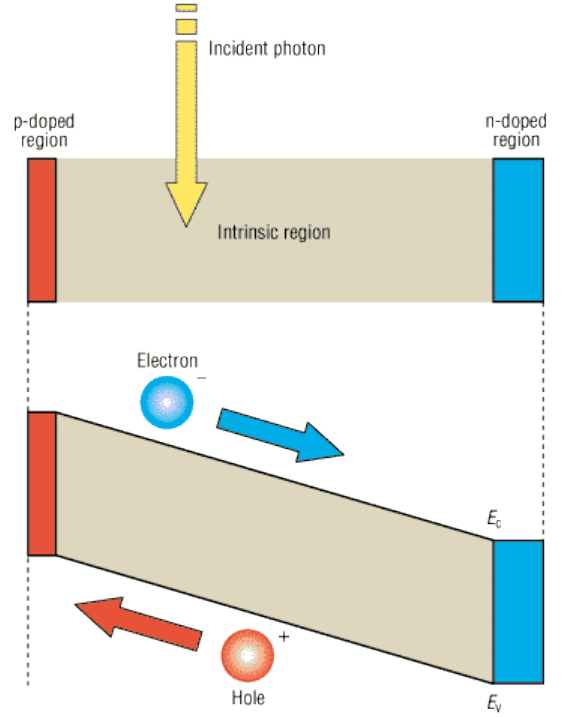
Concentrator Photovoltaics (CPV)

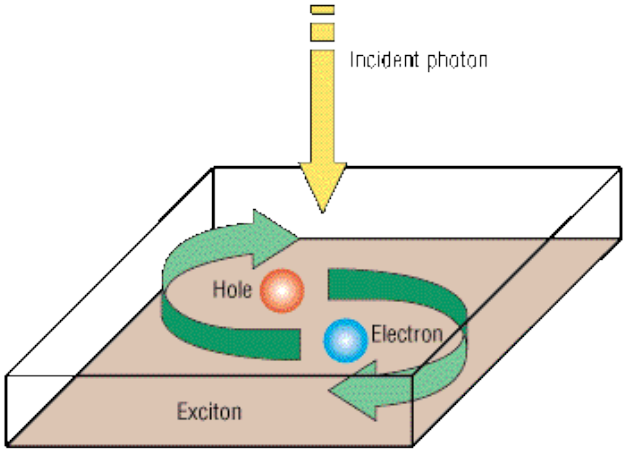
- Flat plate collectors
  - cover large areas with low cost cells
  - don't require external optics
- Concentrator
  - high efficiency cells
  - cover large areas with low cost external optics
- Mid to high-concentration PV systems
  - high-efficiency III-V or Si cells
  - trackers
  - reflective optics or
  - refractive optics
- CPV is inherently system-oriented
- CPV requires direct sun (SW USA)



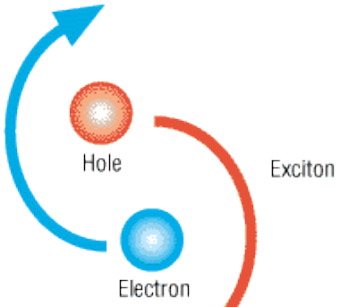
Exciton-Based Materials

Traditional Semiconductor

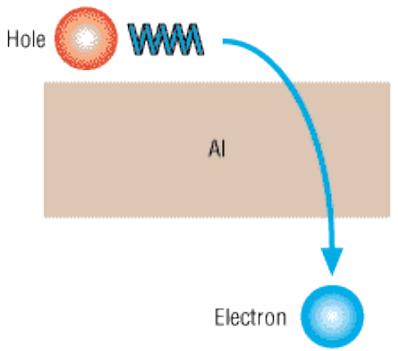




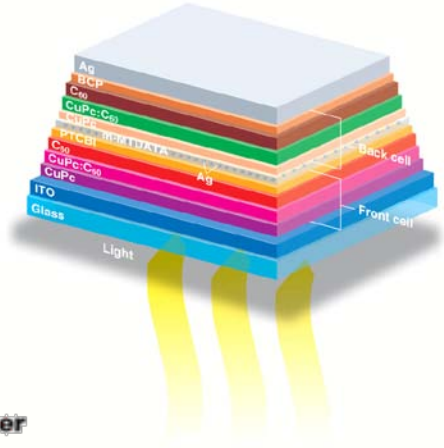
Conducting Polymer

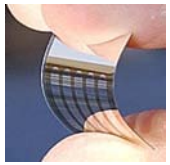


Charge Separation at Interface



Organic Solar Cells





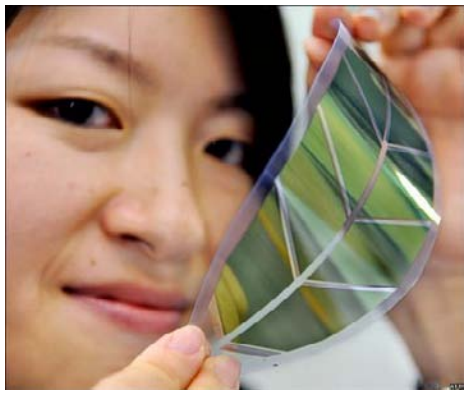
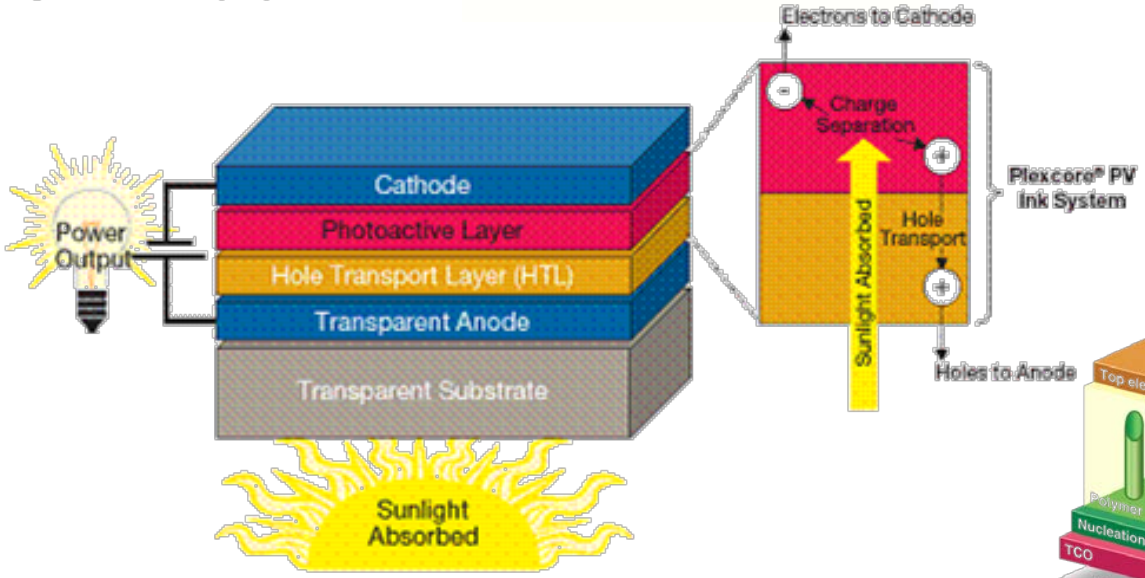
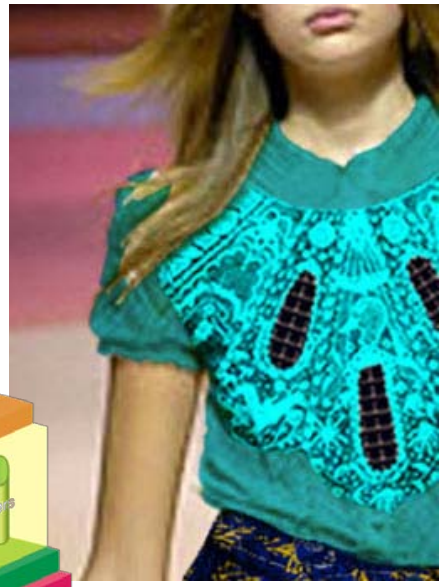
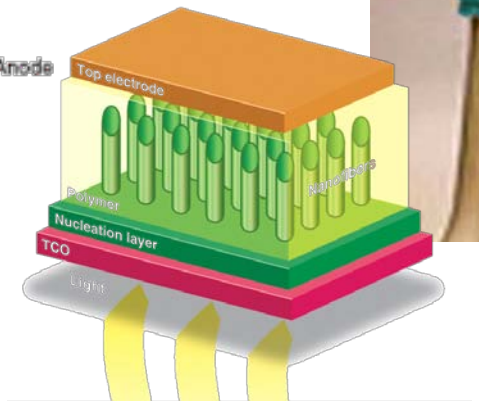


FIGURE 1
Plexcore® PV for Printed Solar Power
Organic Photovoltaic (OPV) Cell Structure

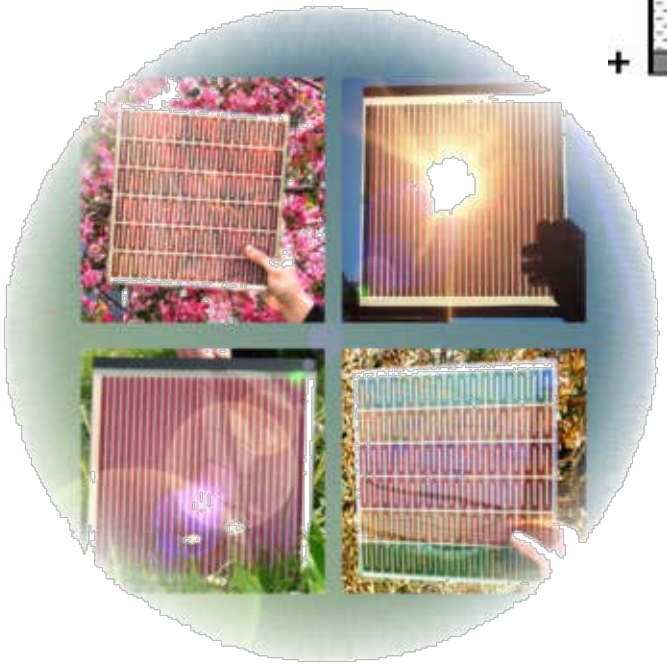


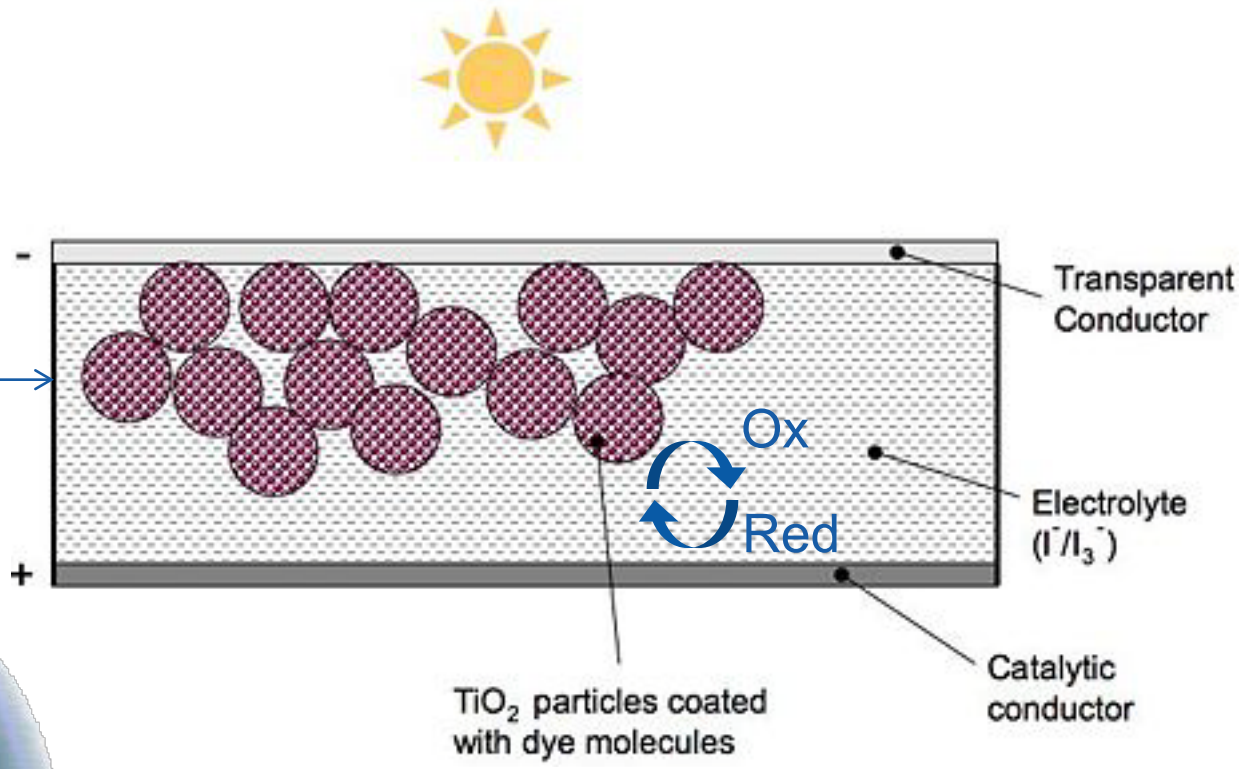




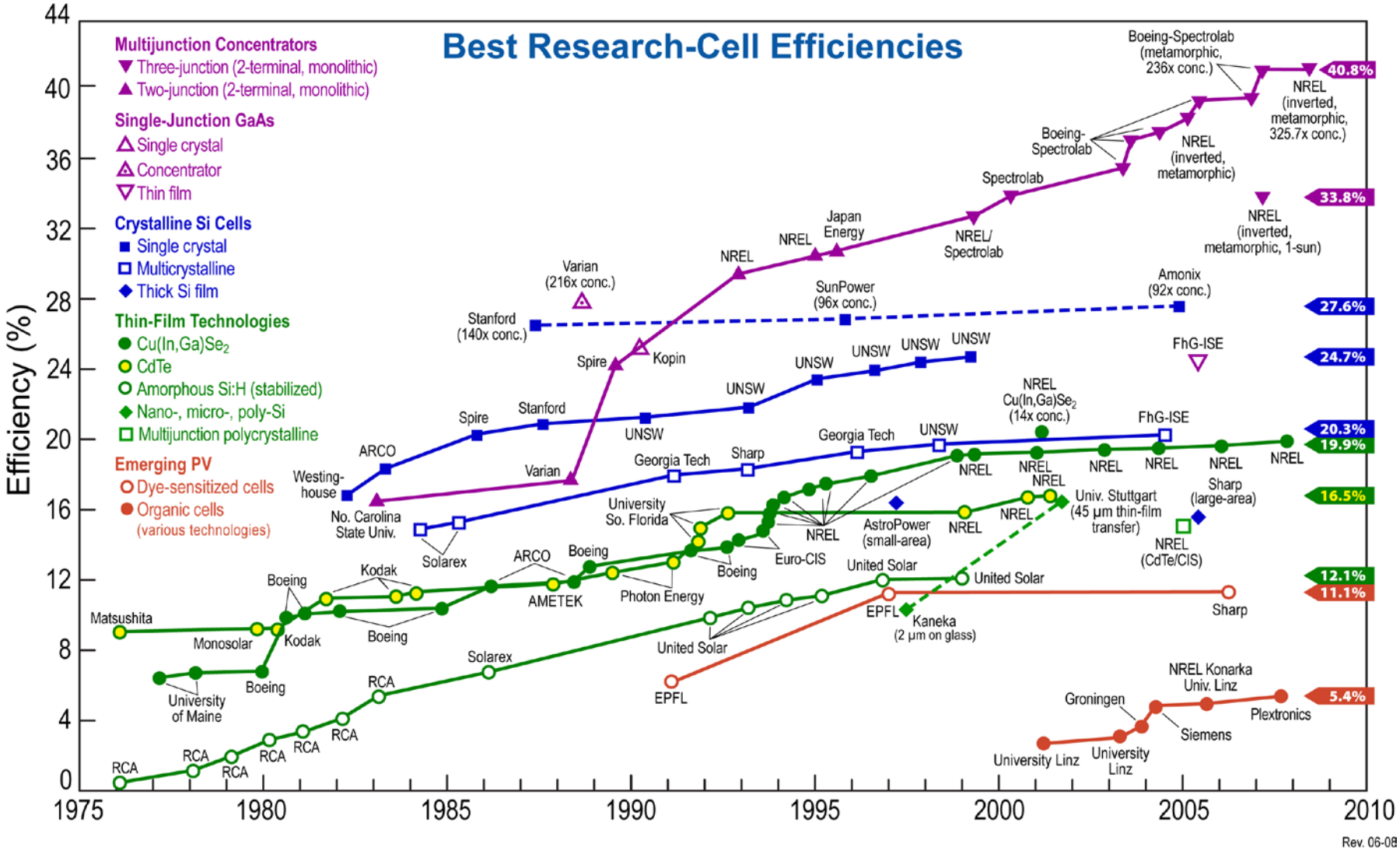
Grätzel (Dye-Sensitized) Cells

High surface area for ruthenium-polypyridine dye

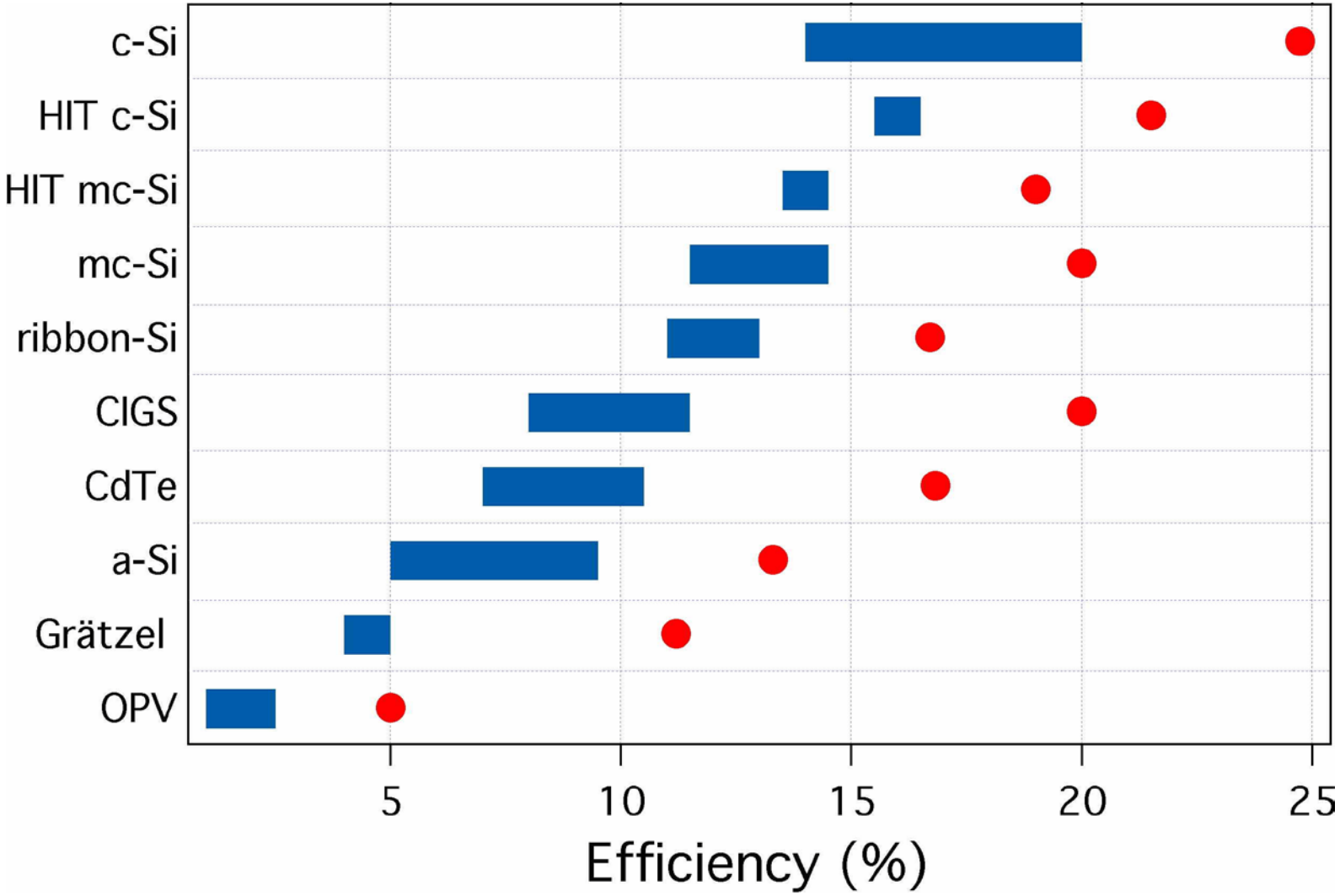




All PV Technologies are Improving

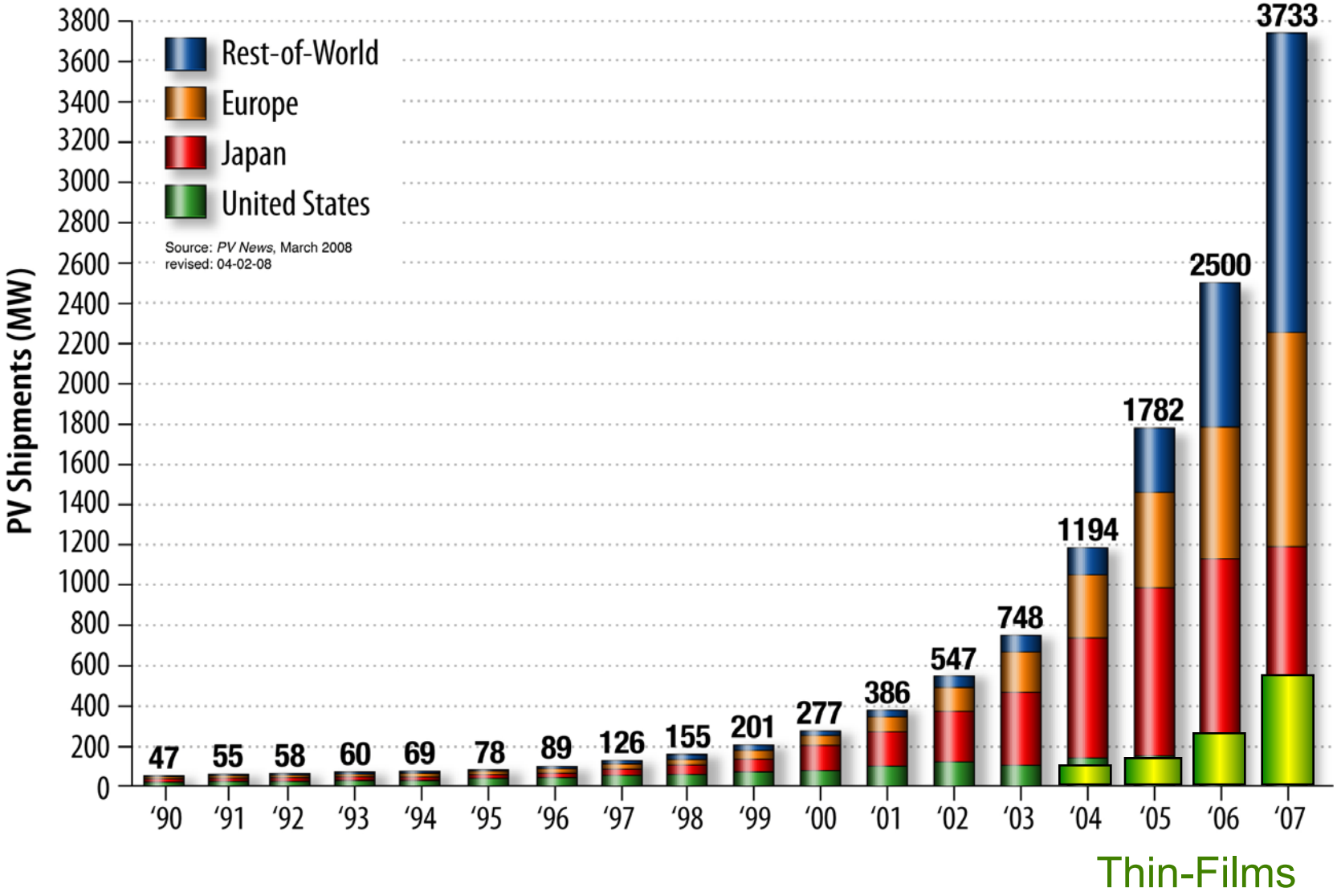


Flat Panel PV Modules & Cells

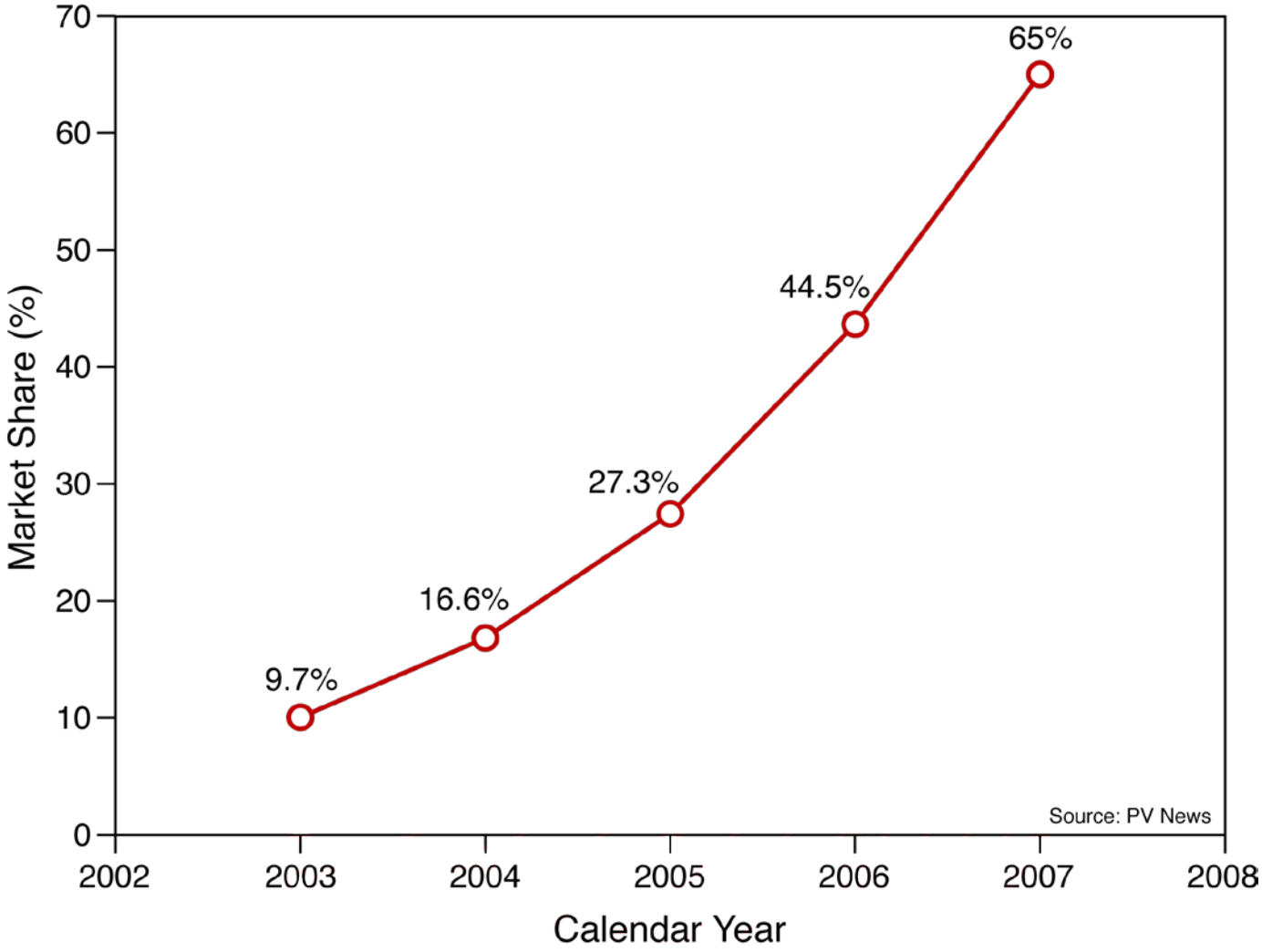


From Citigroup Global Markets, equity research, Applied Materials, Inc, (AMT), 19 Feb. 2008

Worldwide PV Module Production



Thin-Film Market Share in the USA



Conclusions

1. The sun is the BIG energy player
2. PV can (should) be a big part of the Energy Portfolio
3. Some PV types have web-coating applications
   a) crystalline silicon (c-Si) - LOW
   b) amorphous silicon (a-Si:H) - VERY HIGH
   c) cadmium telluride (CdTe) - POTENTIAL
   d) copper indium gallium selenide (CIGS) - HIGH
   e) others (CPV, OPV, DSSC, etc.) – VERY HIGH
4. PV industry is “a mile wide and an inch deep”
5. PV production growing a 35%++ annually

but still very small