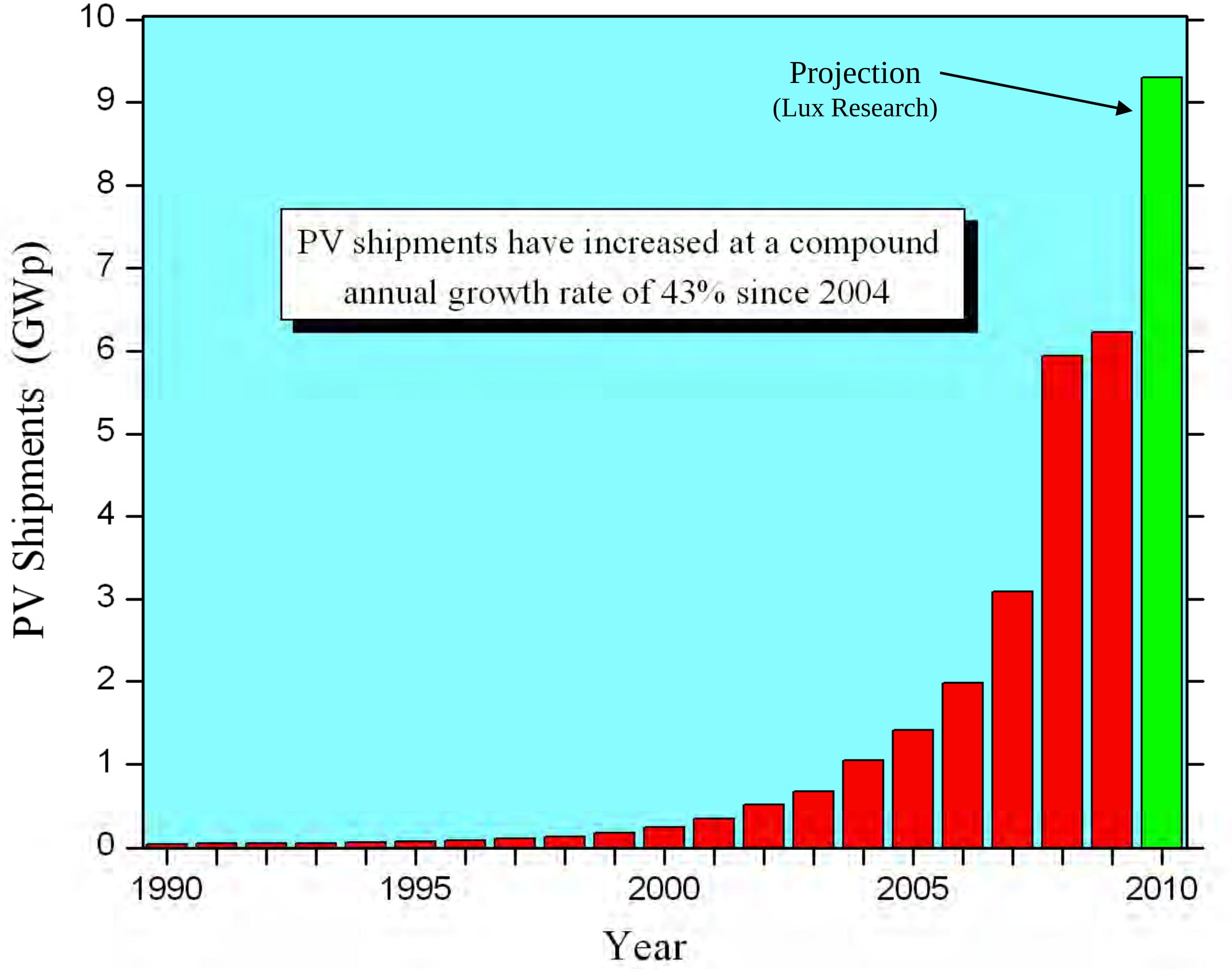
The Status and Future of the Photovoltaics Industry

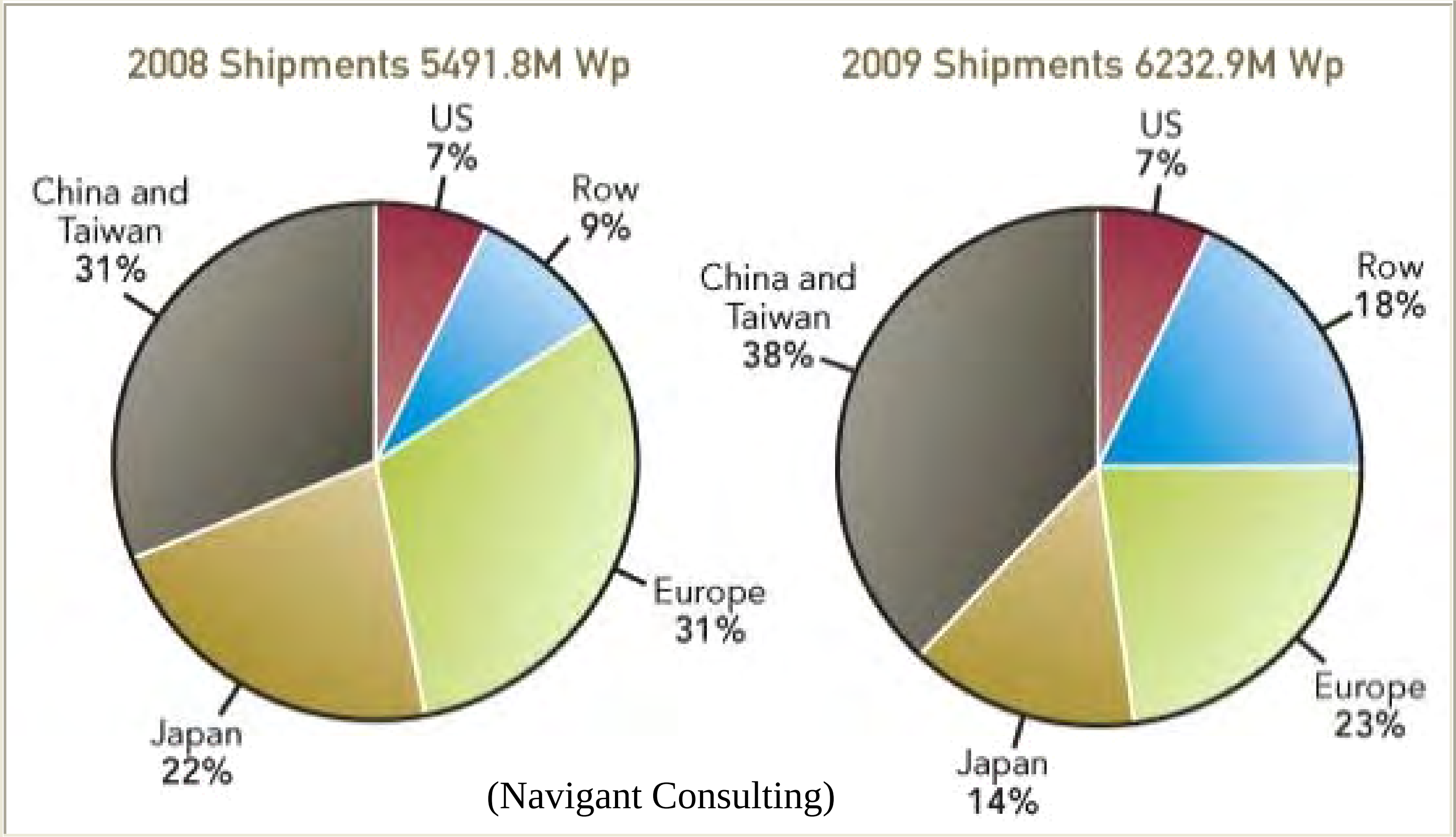
David E. Carlson
Chief Scientist, BP Solar
March 14, 2010

Shipments of Photovoltaic Modules



While PV shipments increase only slightly in 2009, Lux Research forecasts that shipments will increase to 9.3 GWp (or $39 billion) in 2010

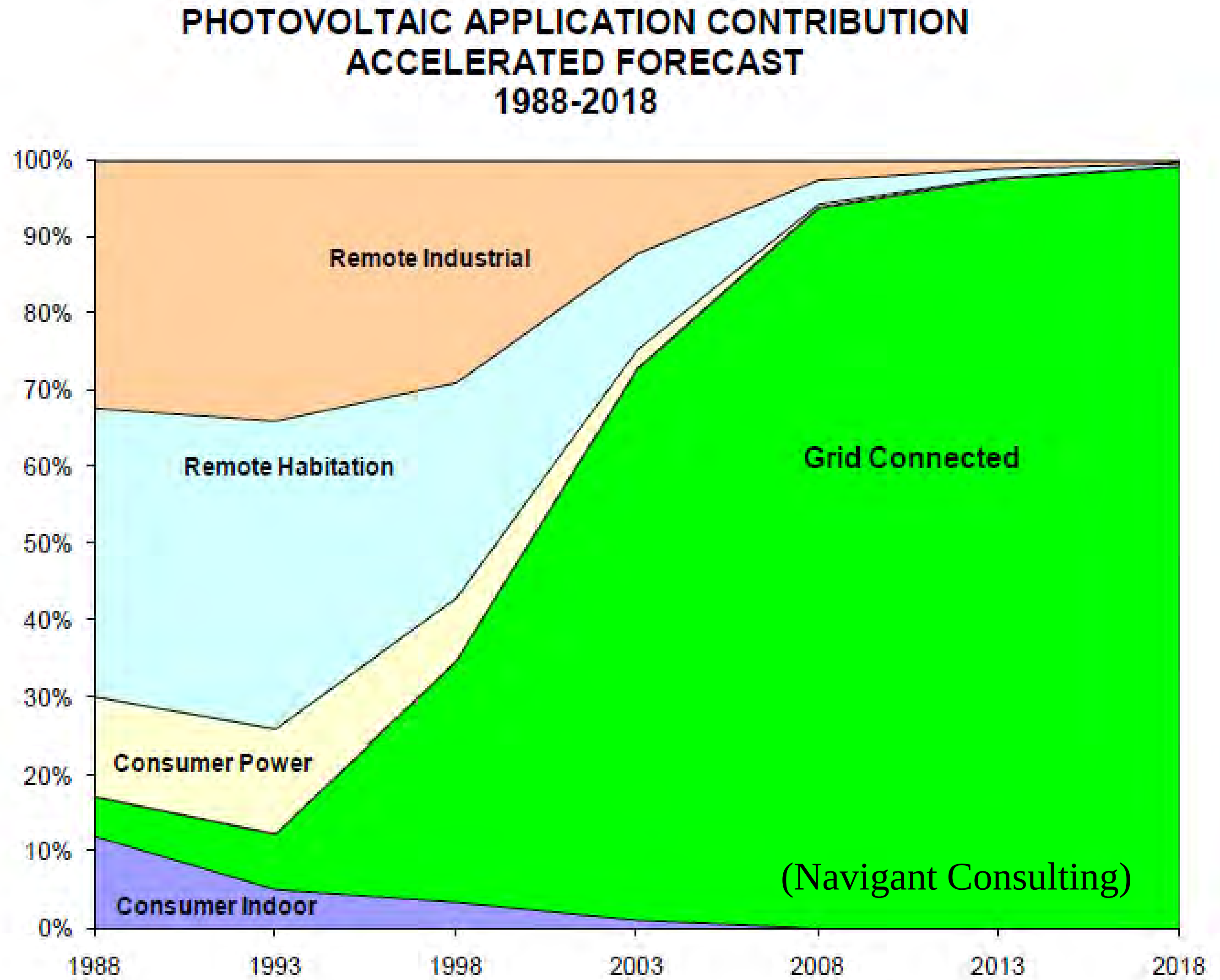
PV Shipments & Countries of Origin



(Navigant Consulting)

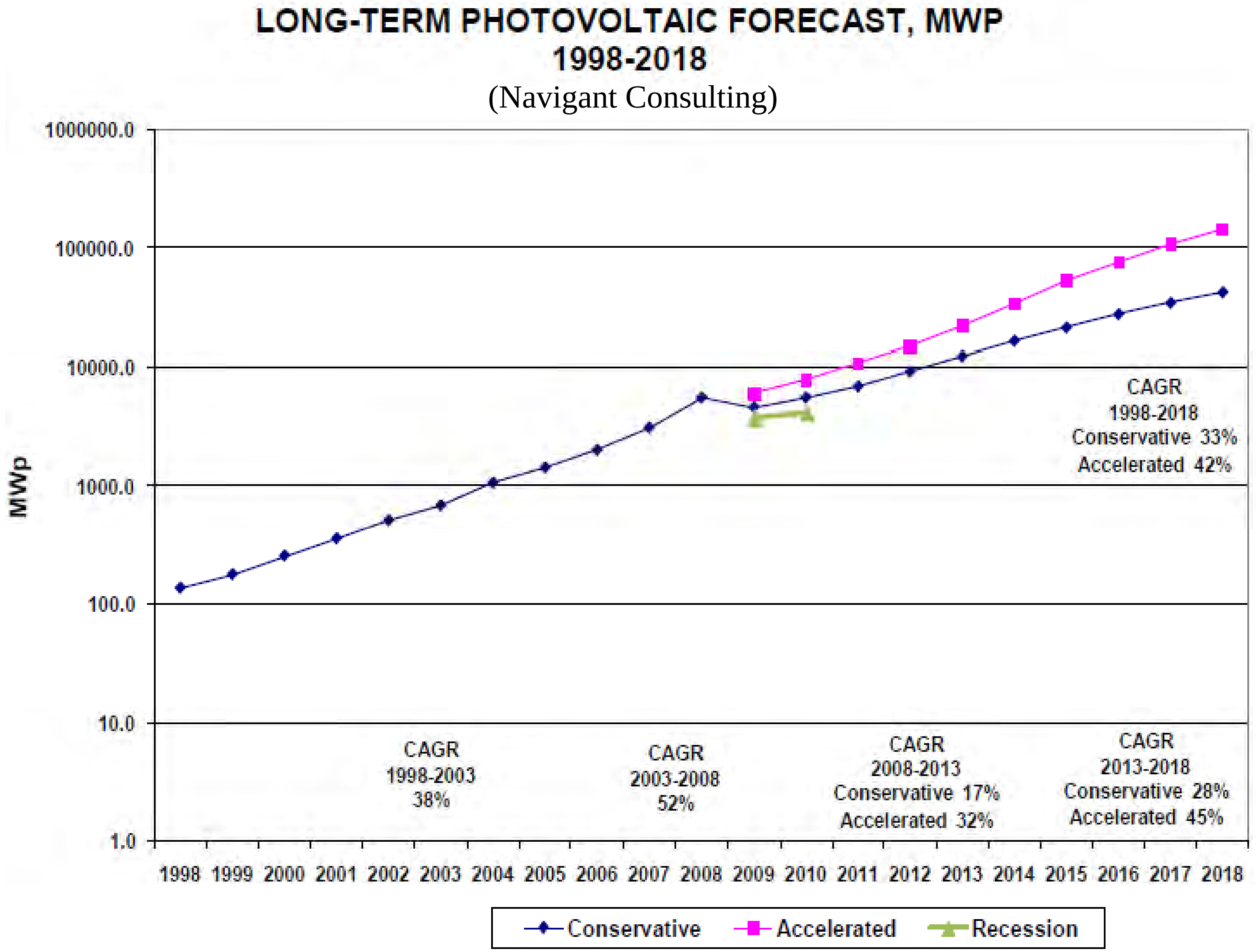
While Europe has been the largest consumer of PV in recent years (> 50% of all installations), China and Taiwan have become the largest producers.

Applications of Photovoltaics



The grid-connected market now dominates the PV business

Projected PV Shipments



Shipments will exceed 100 GWp per year by 2018 if the CAGR = 45%

Forecast for PV Electricity Production

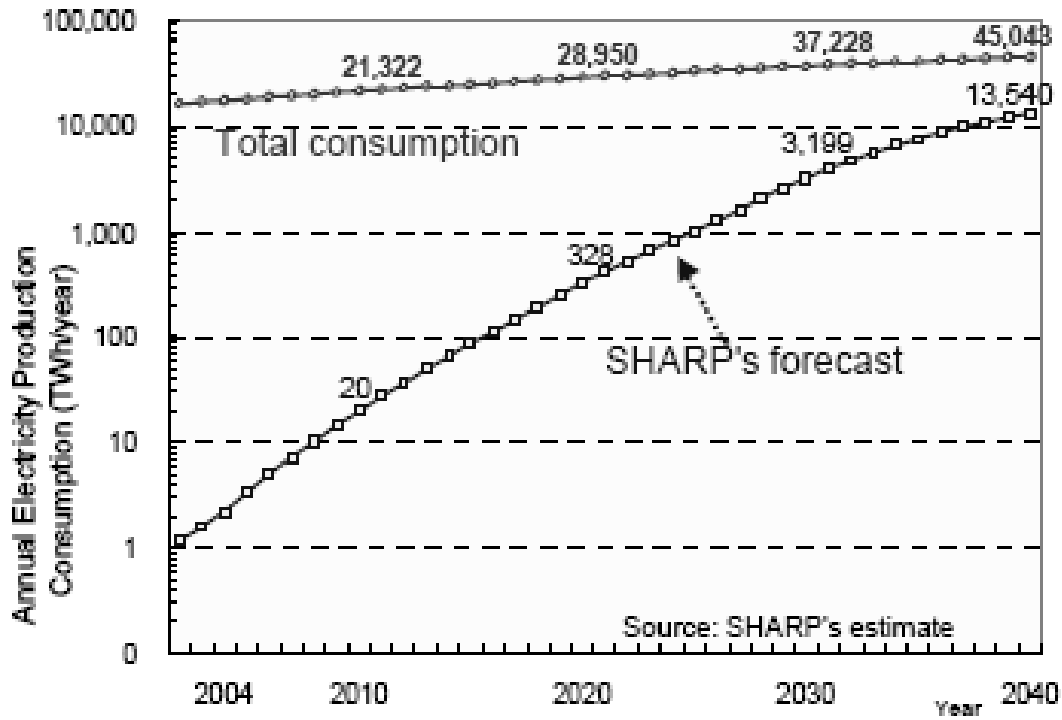


Fig.8 Forecast of world power supply by PV generation

- Sharp forecasts that PV will supply 10% of the world's electricity by 2032
- 3 TWp of solar electricity will reduce carbon emissions by about 1 Gton per year (7 Gtons of carbon were emitted as CO2 in 2000)

The Major Players

Crystalline Si

- Sharp
- SolarPower
- Kyocera
- BP Solar
- Q-Cells
- Mitsubishi
- SolarWorld
- Panasonic (Sanyo)
- Schott Solar
- Isofoton
- Motech
- Suntech
- Evergreen Solar

a-Si/μc-Si

- United Solar
- Kaneka
- Fuji Electric
- Sharp
- Mitsubisihi
- Schott Solar
- SunTech
- EPV
- PowerFilm
- AMAT licensees
- Orelikon licenses

CIGS

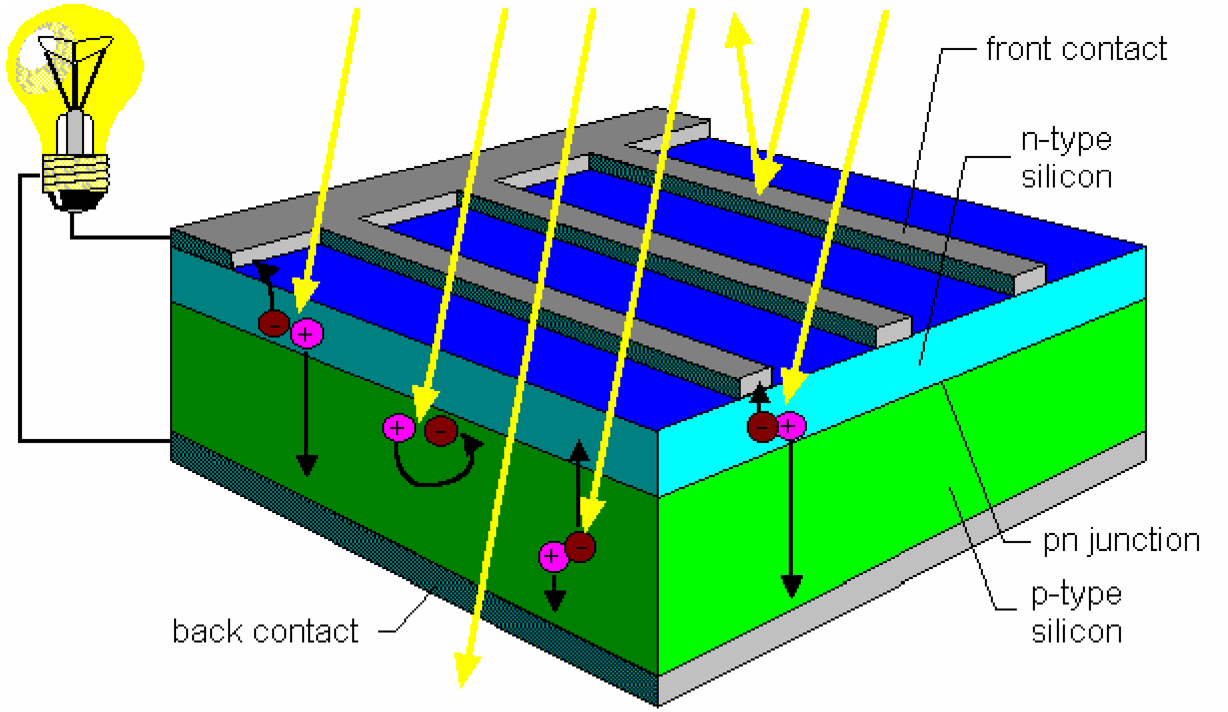
- Avancis
- Solar Frontier
- Wurth Solar
- Global Solar
- Honda Soltec

CdTe

- First Solar
- Antec Solar
- Abound Solar
- PrimeStar Solar
- Calyxo

- There are currently more than 300 companies developing or producing solar cells.
- With prices continuing to decrease, and more companies entering the market, many small companies and start-ups are likely to fail.

The Typical Silicon Solar Cell

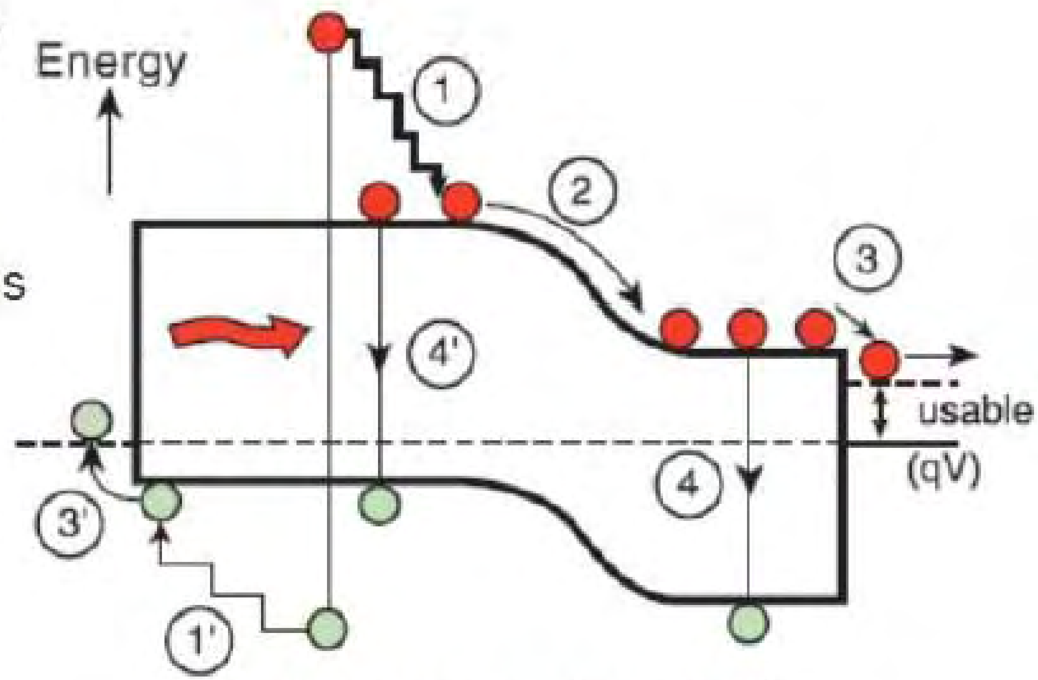


- This device structure is used by most manufacturers today.
  - The front contact is usually formed by $POCl_3$ diffusion
  - The rear contact is formed by firing screen-printed Al to form a back-surface field
- The cell efficiencies for screen-printed multicrystalline silicon cells are typically in the range of 14 – 17%.

Operation of a Solar Cell

Sources of Standard PV-Cell Efficiency Loss

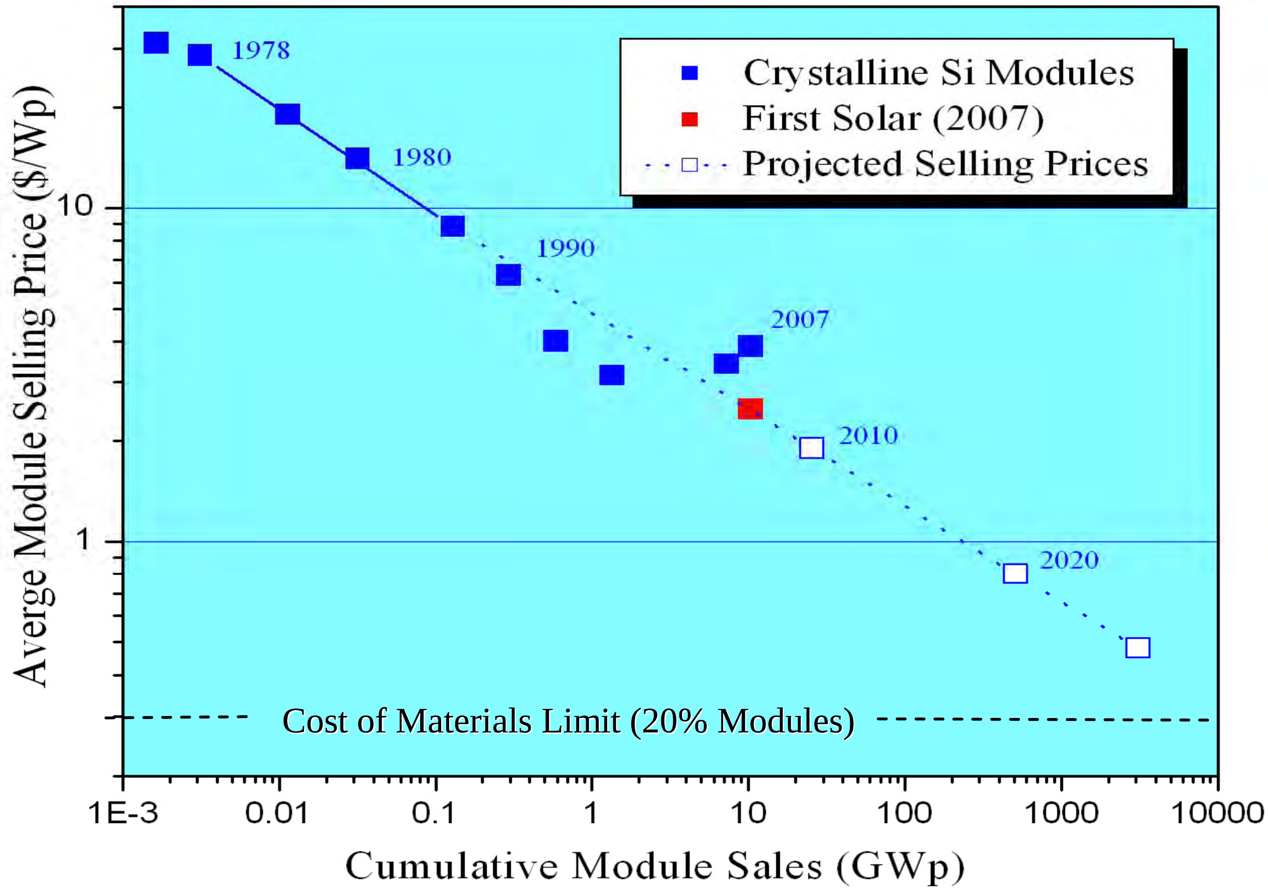
1) Lattice thermalization
2) Junction voltage drop
3) Contact voltage drop
4) Recombination
5) Non absorbed photons



Source: M. Green et al., Univ. New South Wales

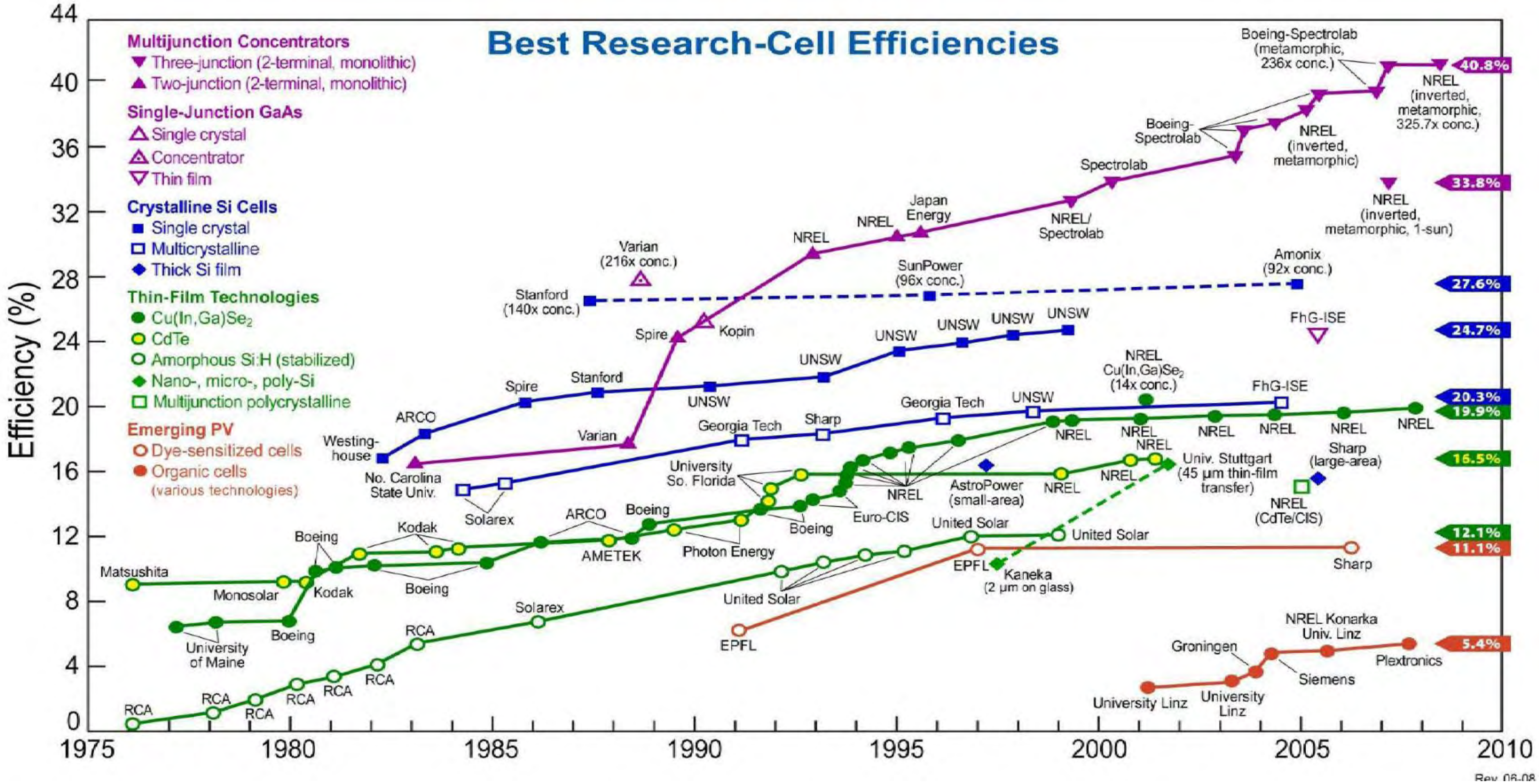
- The theoretical limit for a crystalline silicon solar cell is ~ 29%.

PV Experience Curve



- PV module prices have followed an experience curve with a slope of ~ 80% (a 20% decrease in price with every doubling of cumulative production).

Conversion Efficiencies vs. Time (NREL)



- There has been steady progress in the improvement of conversion efficiencies for a number of PV technologies over the last few decades.

PV Module Conversion Efficiencies

	Modules	Cells (Lab)
➢ Dye-sensitized solar cells	3 – 5%	8.2%
➢ Amorphous silicon (multijunction)	6 - 8%	13.2%
➢ Cadmium Telluride (CdTe) thin film	8 - 10%	16.5%
➢ Copper-Indium-Gallium-Selenium (CIGS)	9 - 11%	19.9%
➢ Multicrystalline or polycrystalline silicon	12 - 15%	20.3%
➢ Monocrystalline silicon	14 - 16%	23.4%
➢ High performance monocrystalline silicon	17 - 20%	24.7%
➢ Triple-junction (GaInP/GaAs/Ge) cell (~ 250 suns)	-	40.7%
➢ Triple-junction (GaInP/GaInAs/Ge) (454 suns)	-	41.1%

✧ For most PV technologies there is a large gap between the best laboratory efficiencies and those achieved in production PV modules

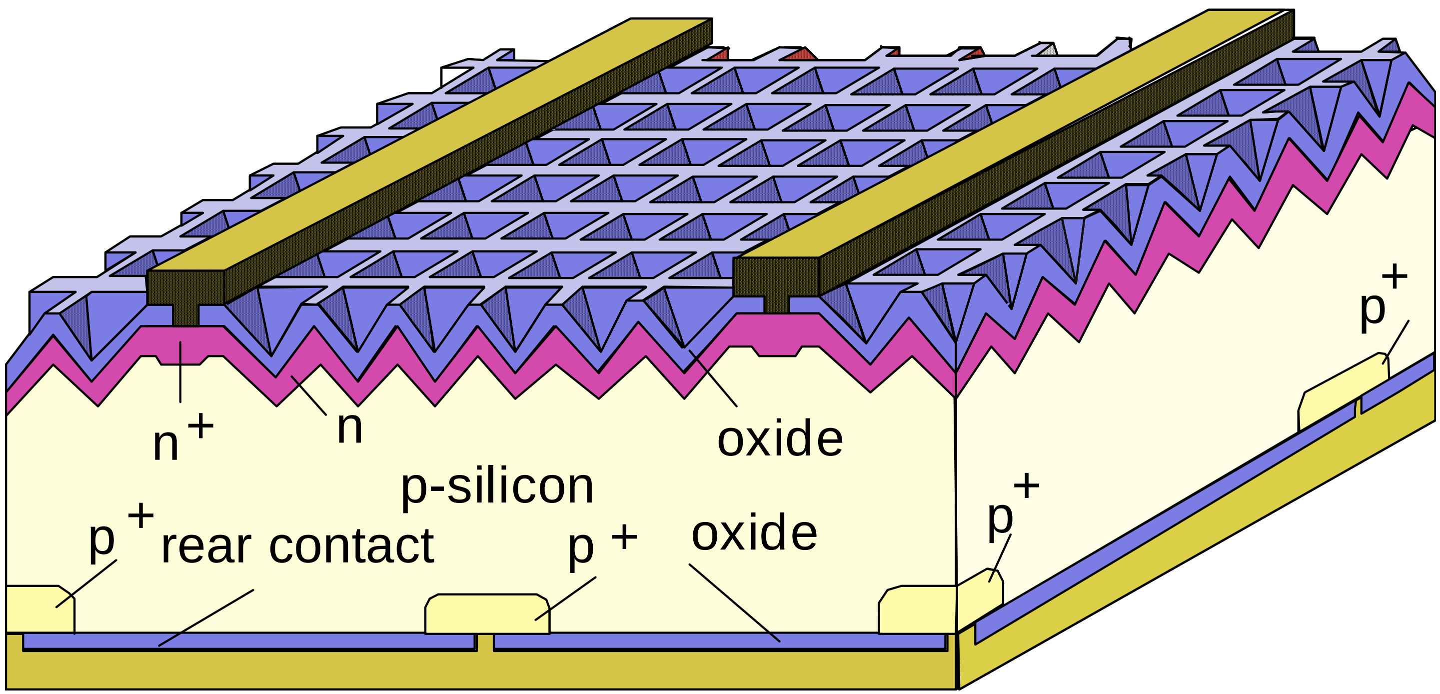
bp solar Paths to Ultra-High Conversion Efficiencies

- Multijunction solar cells (currently used for some thin-film cells and for the highest efficiency cells)
- Multiple absorption path solar cells (impact ionization, multiple exciton generation)
- Multiple energy level solar cells (localized levels or intermediate bands)
- Multiple spectrum solar cells (up and down conversion of photons)
- Multiple temperature solar cells (utilization of hot carriers)

✧ **All these approaches have theoretical efficiency limits > 60%.**

✧ **The theoretical efficiency limit is > 80% for multijunction cells utilizing other high efficiency approaches.**

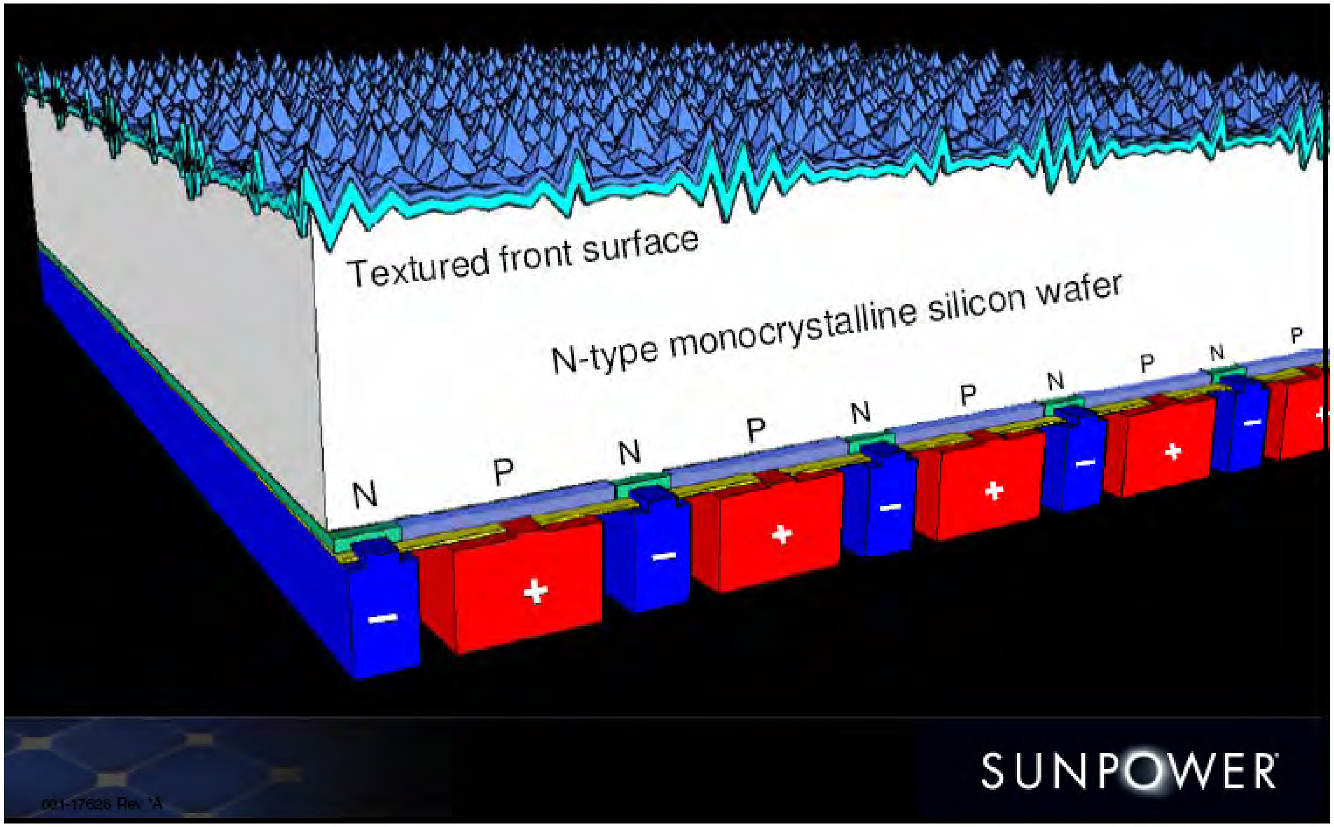
The PERL Solar Cell



PERL Cell Structure

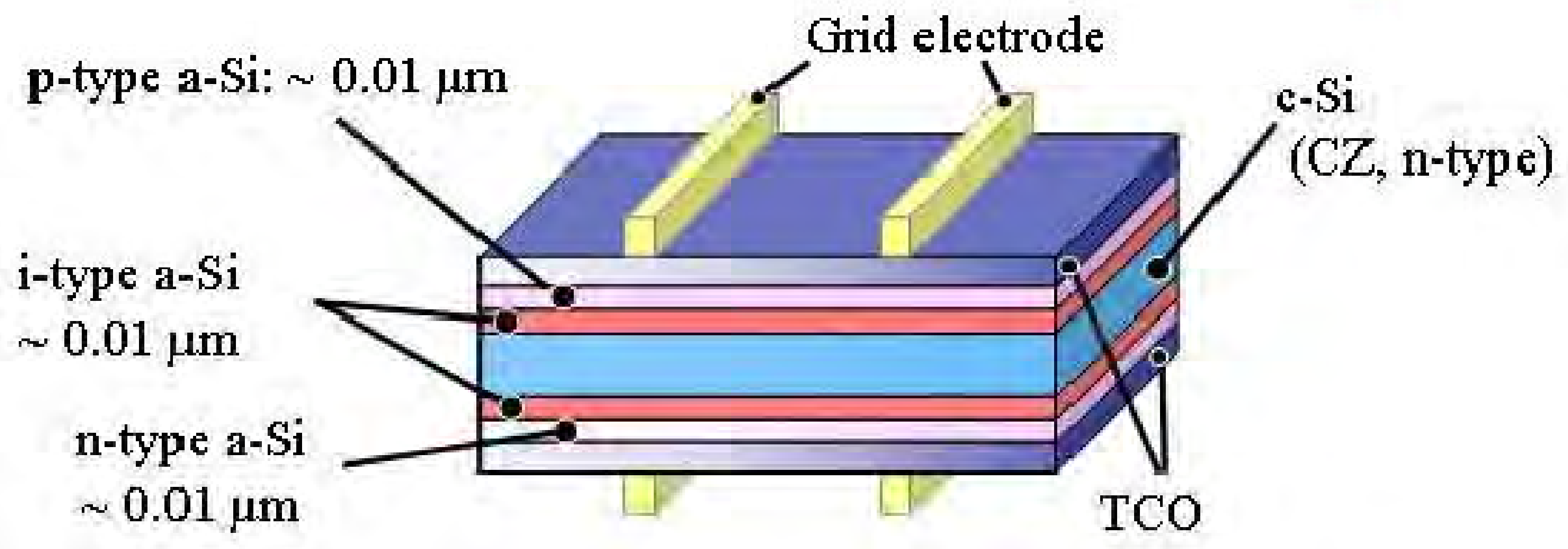
- The PERL solar cell has a passivated emitter with a rear locally diffused base contact, and efficiencies as high as 25% have been obtained with this structure.

SunPower Back Contact Solar Cell



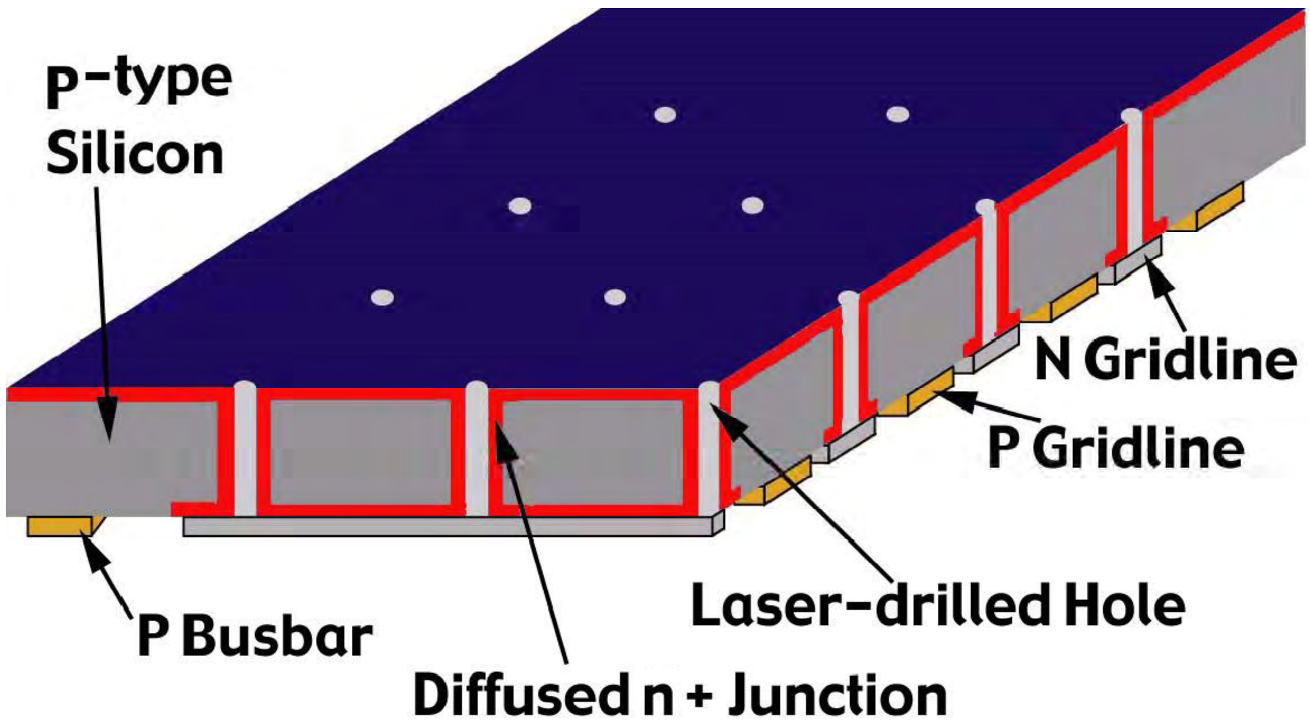
- The SunPower cell has all its electrical contacts on the rear surface of the cell.
- Production cells ~ 22.4% efficiency; new prototypes at 23.4%.
- Diffusion lengths > 3 x cell thickness (using 145 μm thick CZ-Si at end of 2008).

Sanyo HIT Solar Cell



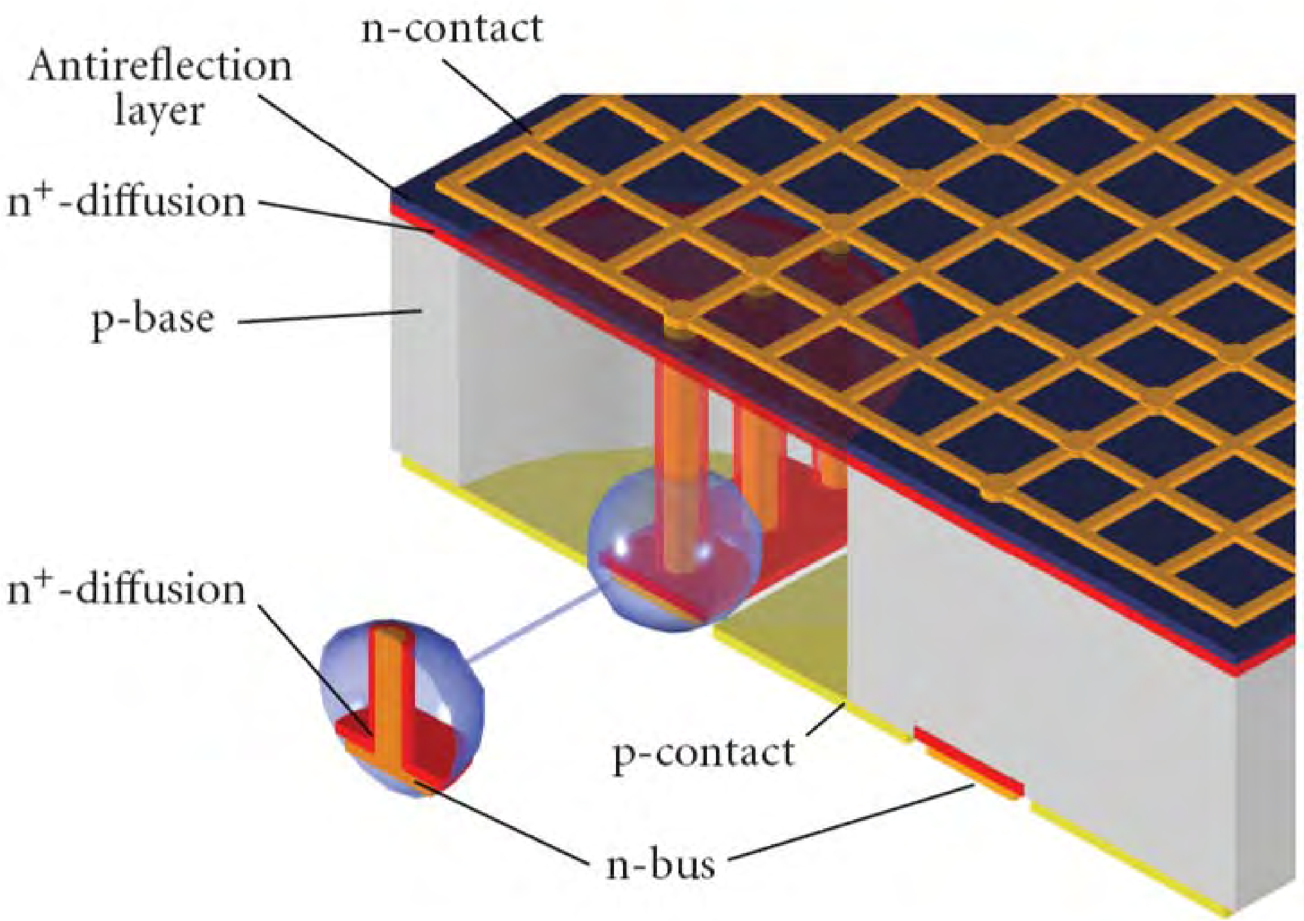
- The HIT cell utilizes amorphous Si intrinsic layers (~ 5 nm) as passivation layers. The cell is symmetric except for the a-Si p^+ emitter layer (~ 10 nm) on the front and the a-Si n^+ contact layer (~ 15 nm) on the rear.
- Best lab efficiency = 22.3% (open-circuit voltages as high as 739 mV).

The Emitter-Wrap-Through (EWT) Cell



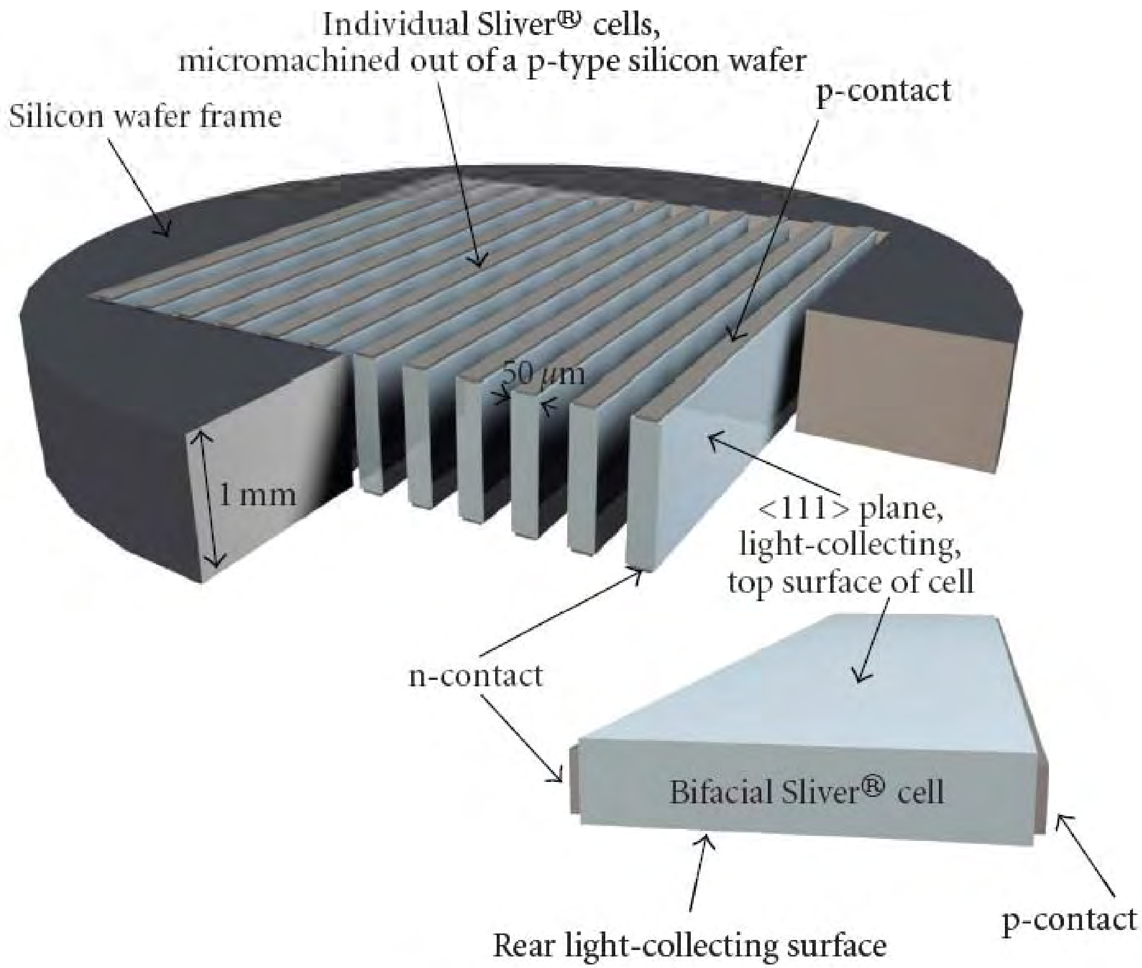
- The EWT cell has ~ 45,000 holes per wafer with cell efficiencies ~ 15%.
- Advent Solar started selling limited quantities of EWT cells in 2007, but encountered difficulties and the assets were acquired by Applied Materials

Metal-Wrap-Through (MWT) Solar Cell



- Photovoltech is commercializing the MWT solar cell; efficiencies ~ 15%.

The Sliver® Solar Cell

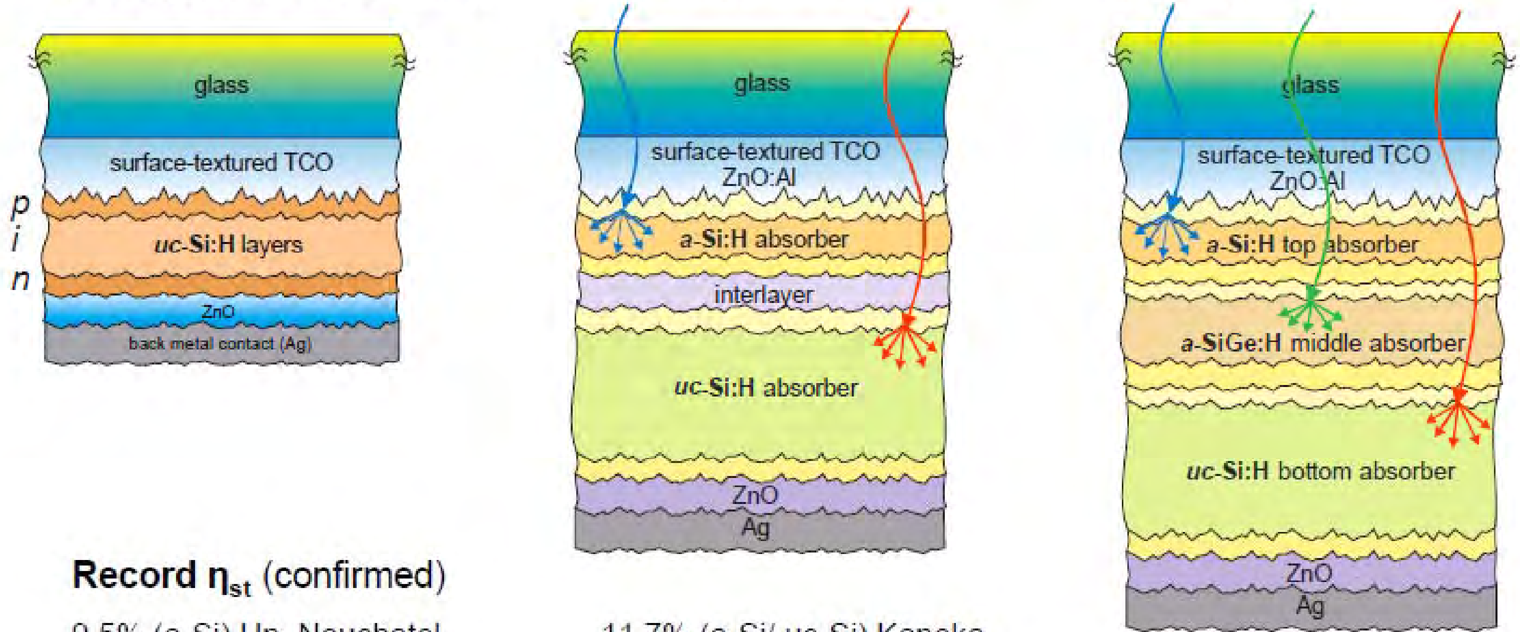


- Origin Energy (Australia) is commercializing the Sliver® Solar Cell.
- They have demonstrated cell efficiencies > 20%.

Thin Film Silicon Solar Cells

Delft Univ. of Technology

single-junction	double-junction	triple-junction
amorphous (a-Si:H) microcrystalline (uc-Si:H)	micromorph a-Si:H/uc-Si:H	e.g. a-Si:H/a-SiGe:H/ uc-Si:H

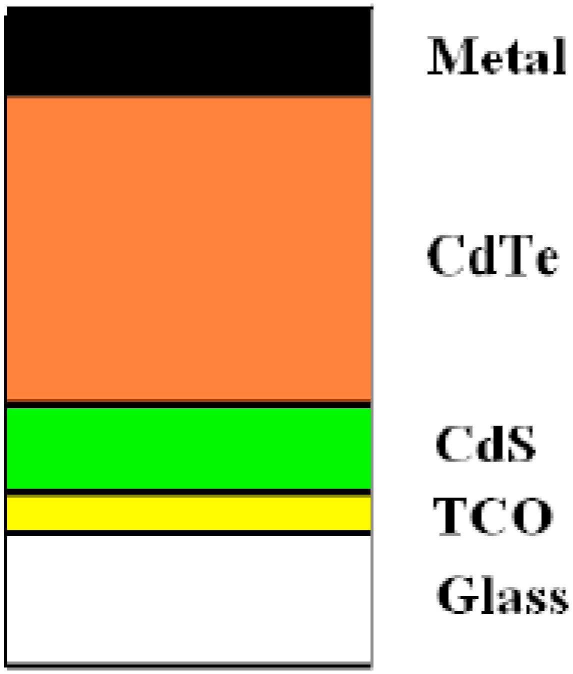


Record η_{st} (confirmed)

9.5% (a-Si) Un. Neuchatel	11.7% (a-Si/ µc-Si) Kaneka	
10.1% (µc-Si) Kaneka	12.4% (a-Si/a-SiGe) USSC*	13.0% (Si/SiGe/SiGe) USSC*

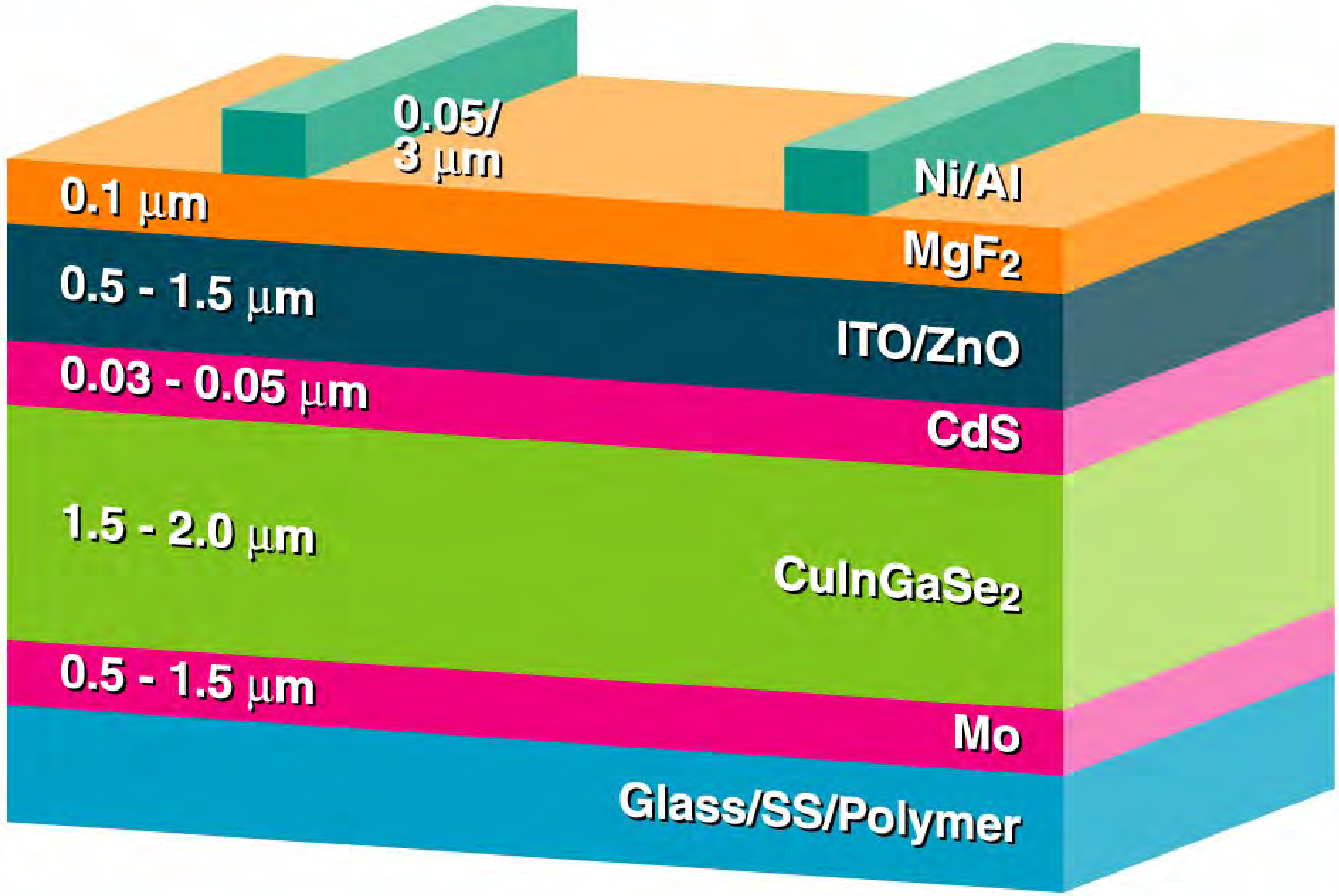
- Companies such as Sharp and Mitsubishi are developing variants of the micromorph solar cell.
- Applied Materials and Oerlikon have each sold several manufacturing lines that can produce single-junction amorphous silicon and micromorph solar cells.

Cadmium Telluride Solar Cells



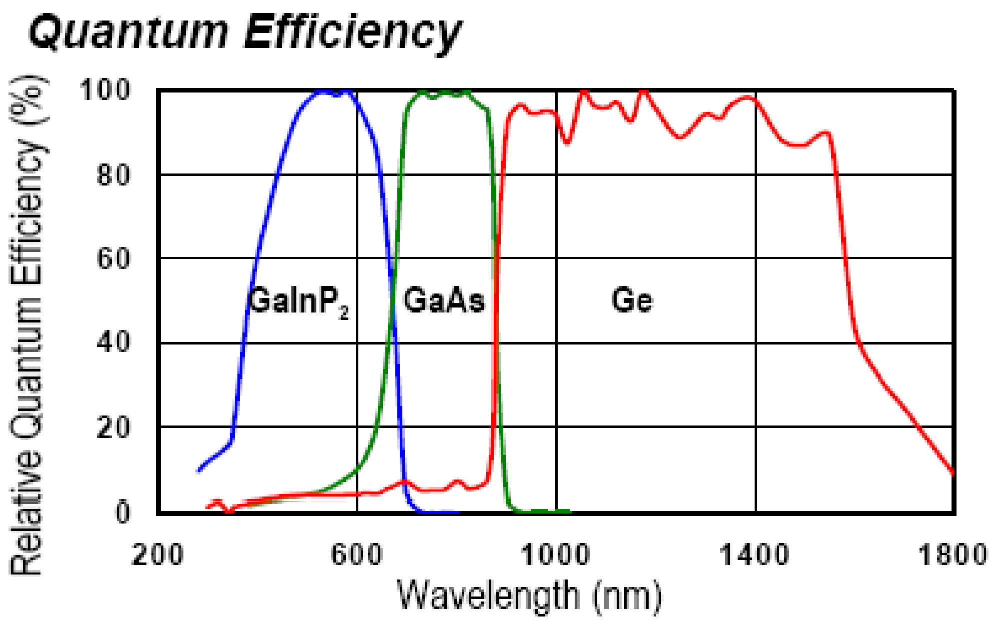
- The CdS/CdTe heterojunction solar cell is typically formed by using a chemical bath technique to deposit the CdS and close space vacuum sublimation to deposit the CdTe.
- Toxicity of Cd is perceived by some to be an issue.
- Best lab efficiency = 16.5%.
- First Solar has reported manufacturing costs of ~ \$0.94/Wp.
- First Solar shipped more than 1 GWp of CdTe modules in 2009 with an average selling prices of ~ \$2/Wp.

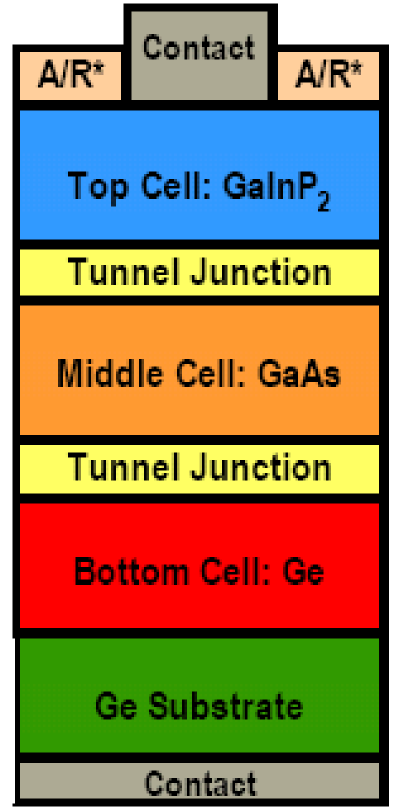
Copper-Indium-Gallium-Diselenide Cell



- NREL has demonstrated an efficiency of 19.9% for the CIGS solar cell.
- Typically requires relatively high temperature processing (> 500°C).

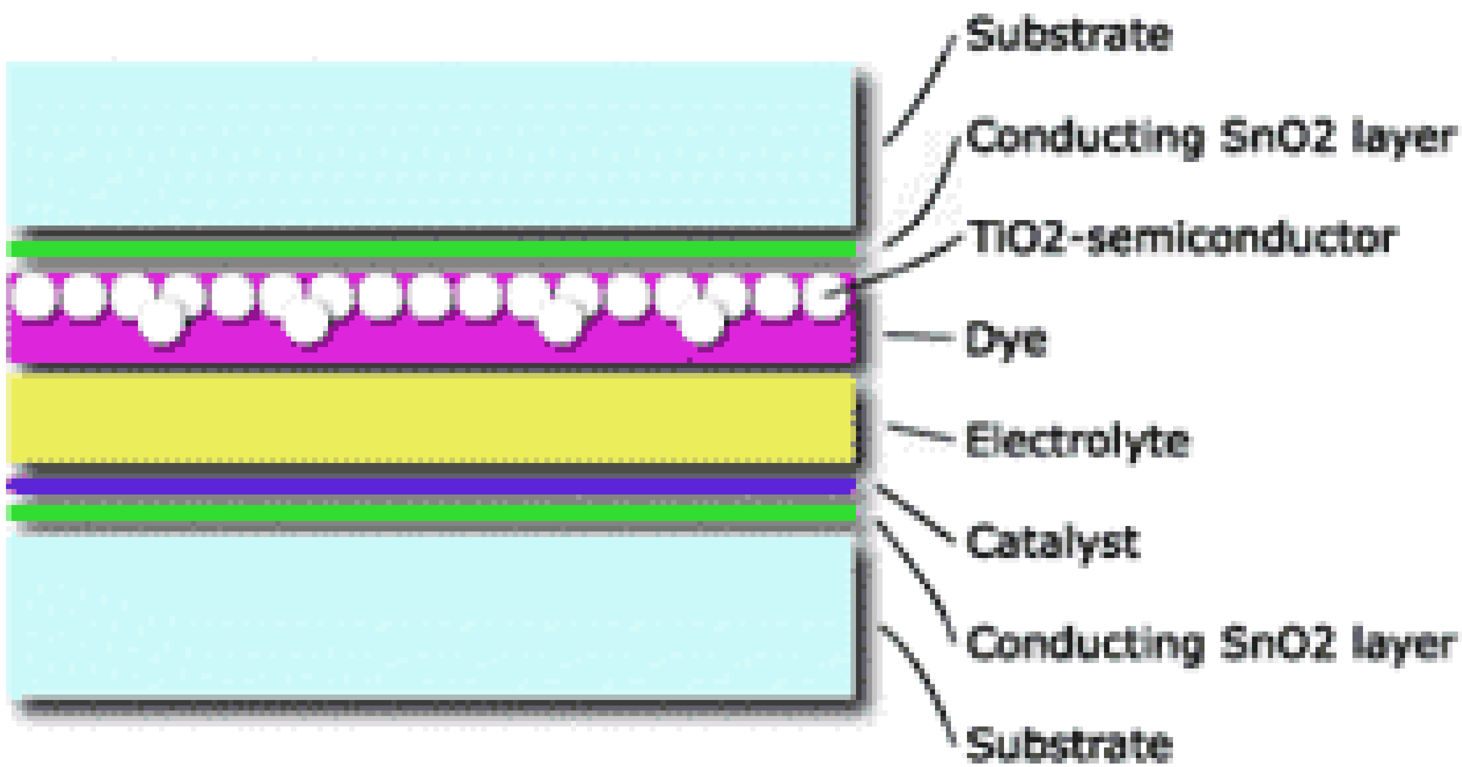
Spectrolab's Triple-Junction Solar Cell





- Spectrolab has reported a conversion efficiency of 40.7% with this solar cell structure operating at ~ 250 suns.
- More recently Fraunhofer ISE has obtained an efficiency of 41.1% with a triple-junction cell operating at ~ 454 suns.

Dye-Sensitized Solar Cells



- Dye-sensitized solar cells utilize a few monolayers of ruthenium-based dye molecules on titanium oxide particles in an electrolyte.
- The best initial efficiency for small cells is 12.3% but the stabilized efficiency is closer to 8%.

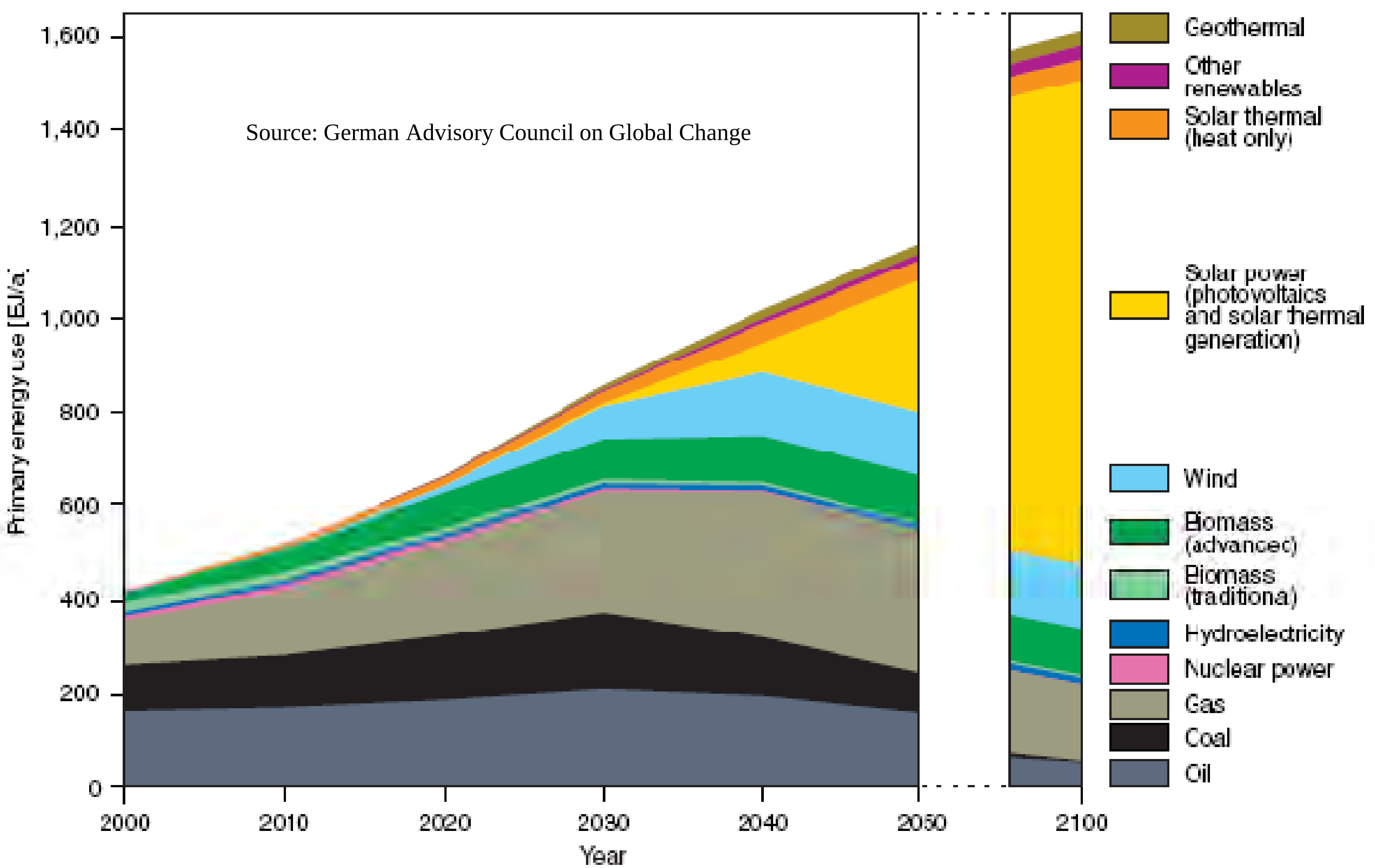
Residential Building-Integrated PV

- Building-integrated PV may become pervasive in the next few decades.

Large Grid-Connected PV Arrays

- The levelized cost of electricity should fall to ~ 6 ¢/kWh by 2015 for large grid-connected arrays

Solar Energy – the Long-Term Solution?



- Some forecasts predict that solar will provide most of our energy needs in the latter half of this century.

Projections for the Future of PV

- The levelized cost of PV electricity could fall to ~ 6 ¢/kWh by 2015
- Disruptive technologies with theoretical limits of > 60% may emerge in the next few decades
- Assuming a CAGR of 35% (average over the last few decades), the cumulative PV production would be ~ 3.5 TWp by 2026.
- 3 TWp of solar electricity will reduce carbon emissions by about 1 Gton per year (7 Gtons of carbon were emitted as CO_2 in 2000)
- Thus, by about 2030 PV could be producing about 10% of the world's electricity and start to play a major role in reducing CO_2 emissions