Emerging Research on Low-Cost Solar Energy Harvesting for Photocatalytic Pollution Treatment and Solar Cells

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Emerging Research In:

Photocatalysis

- The use of light energy to effect chemical change, e.g.:
  - Light-activated degradation of pollutants in water or air
  - Use of light energy to split water into H_2 and O_2

Recent developments:

- Better use of sunlight
- Higher reaction rates
- New applications

Photovoltaics

- Direct conversion of radiant solar power to electrical power
- Reduces air pollution by displacing combustion of fossil fuels

Recent developments:

- Major cost reductions due to:
  - Improvements in silicon PV manufacture
  - Dye-sensitized solar cells
  - Perovskite solar cells breakthrough

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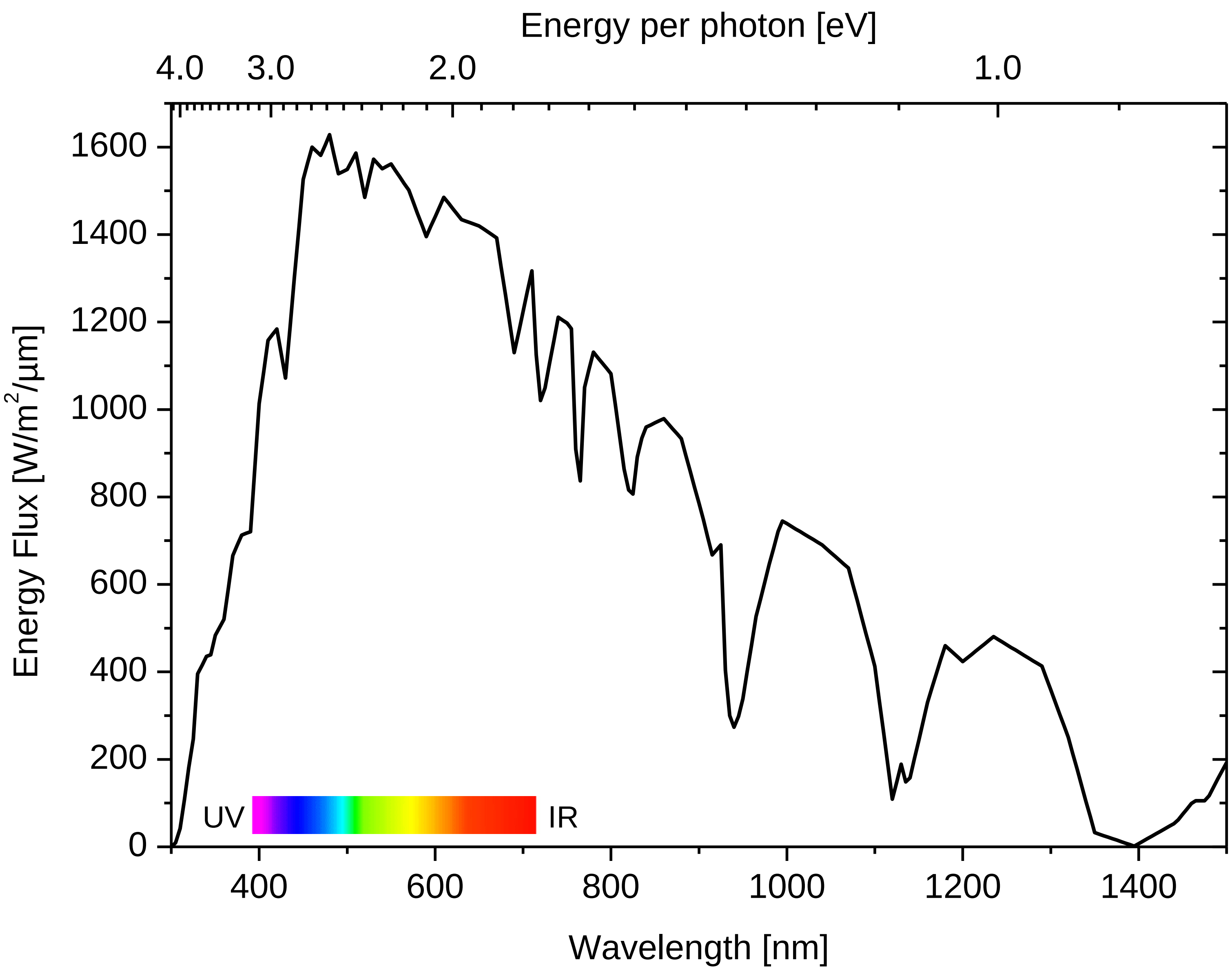
The Sun

The Solar Spectrum



Total power of “standard” full sunlight:

1000 W/m^2

Nanoparticulate titanium dioxide (TiO_2)

Properties

- white solid
- insoluble
- stable
- non-toxic
- cheap
- wide commercial use

Source: Thiele Technologies

Semiconductor

- Absorbs photons with energy > 3.2 eV
- Corresponds to wavelength < 385 nm (UV)

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Photocatalysis

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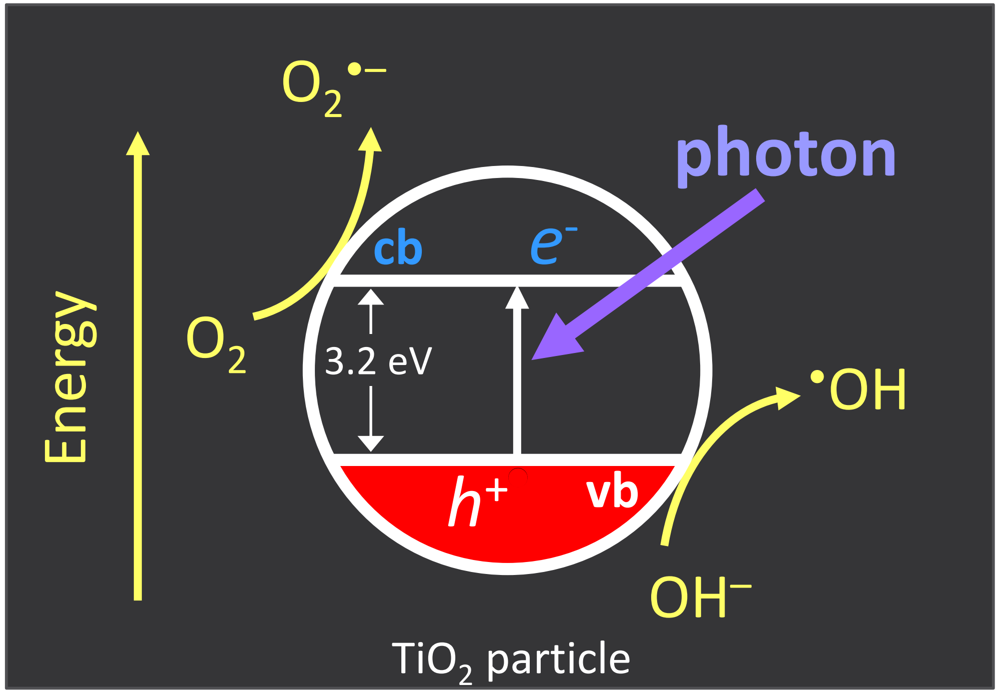
Mechanism of Photocatalysis



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Utility of photocatalytic pollution treatment

Advantages

- Able to degrade nearly any organic compound, and many inorganic compounds
  - Hydrocarbons
  - Highly chlorinated organics
  - NO_x
- Able to sterilize surfaces
- Requires no continuous chemical inputs
- Can be powered by UV lamps or by sunlight
- TiO_2 material is cheap and plentiful

Disadvantages

- Light-blocking deposits can make surface ineffective
- Some degradation is undesirable, e.g. plastic substrates, organic binders, etc.
- Low reaction rates under sunlight
- Process can be expensive due to energy consumption of UV lamps for high rates

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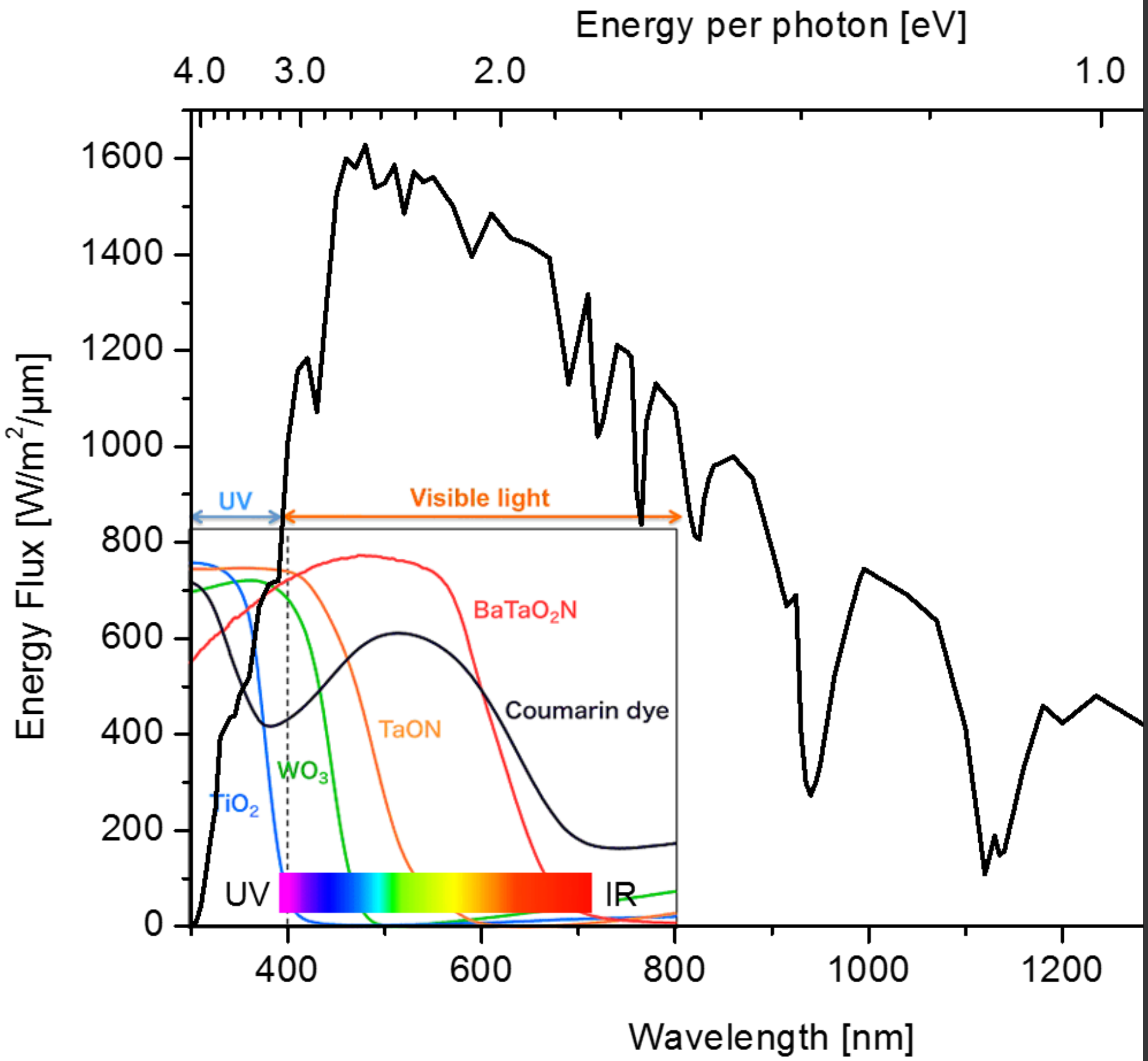
Expanding the spectral window

- Modifications of TiO_2:
  - Doping with nitrogen
  - Hydrogenation of surface
  - Addition of organics to surface
    - Conjugated polymers
    - Graphene-like carbon nitride
- Alternatives to TiO_2
  - Bismuth vanadate ($BiVO_4$)
  - Tungsten oxide (WO_3)
  - Zinc oxide (ZnO)
  - Zeolites



Air applications of photocatalysis

- Degradation of VOCs
- $NO_x \rightarrow N_2$ or HNO_3
- $SO_2 \rightarrow SO_4^{2-}$
- $CO \rightarrow CO_2$
- $O_3 \rightarrow O_2$
- Deodorization
- Indoor air purification

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Solar Photovoltaics

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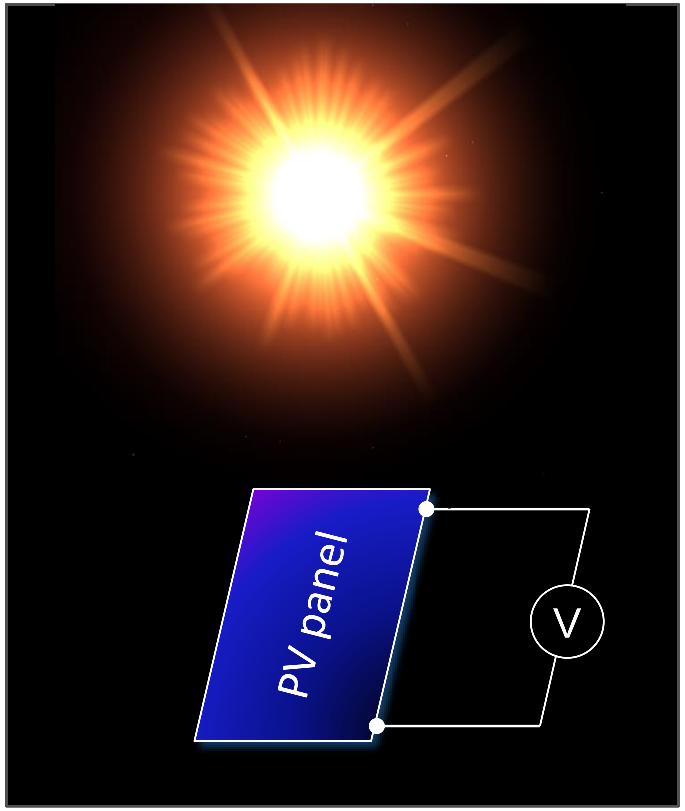
Solar Power Conversion Efficiency (PCE)



Theoretical limit for any solar cell
with a single light-absorbing material:

~ 33%

$$Efficiency = \frac{Power\ out\ (electrical)}{Power\ in\ (solar)} = \frac{Electrical\ power\ (\mathrm{W/m^2})}{1000\ \mathrm{W/m^2}}$$

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PV Landscape as of 2012

Technology	Record Lab PCE
Crystalline Silicon (c-Si) • Dominant commercial technology • Silicon is a very abundant element • Somewhat expensive to manufacture in required purity • Requires thick layers (~250 µm)	25.0%
Gallium arsenide "III-V" tandem • Very high-efficiency • Very high cost • Practical only for space applications	36.9%
Cadmium telluride (CdTe) • Thin-film (~10 µm), low-cost manufacturing • Similar to c-Si in $/W • Concerns with toxicity of Cd, scarcity of Te	16.7%
Copper indium gallium selenide (CIGS) • Thin-film (~10 µm), low-cost but challenging to scale-up • Also contains some non-abundant elements (In, Se)	20.3%
Dye-sensitized solar cell (DSSC) • Based on nano-TiO_2 plus organic dye molecules • Radically different principle of operation • Possibility of very low cost	11.4%

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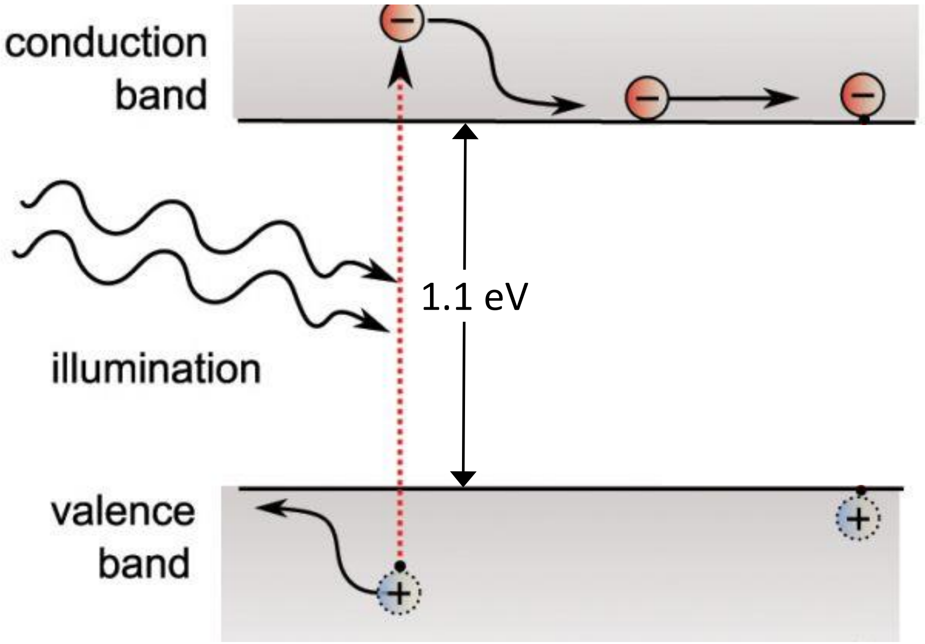
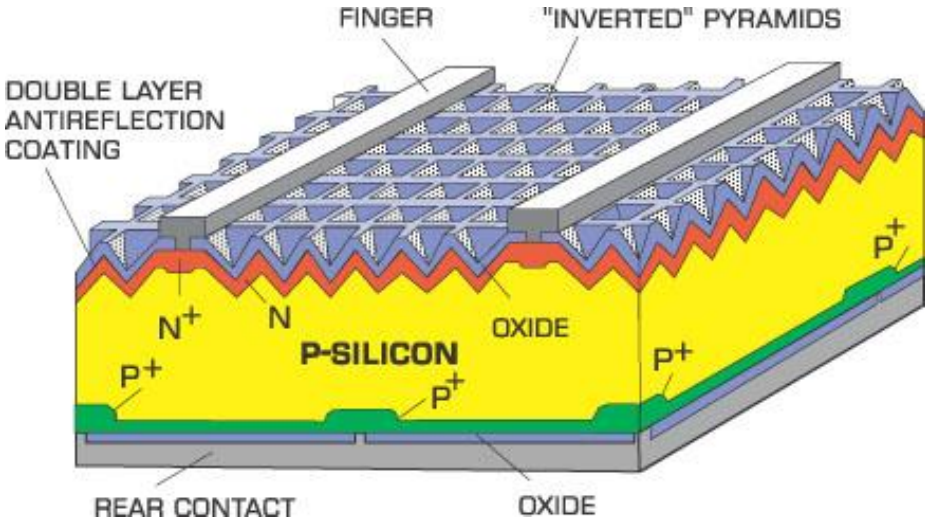
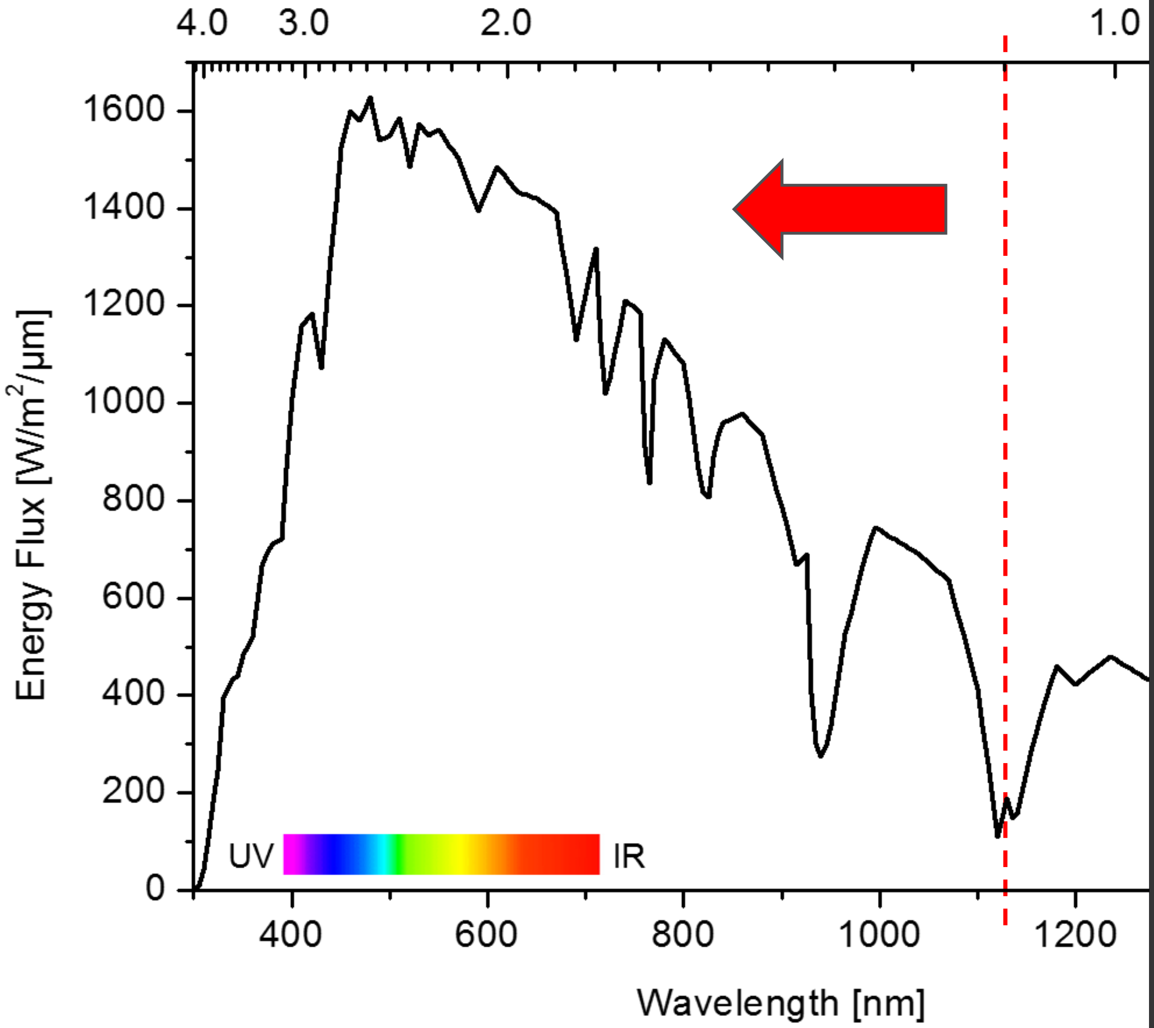
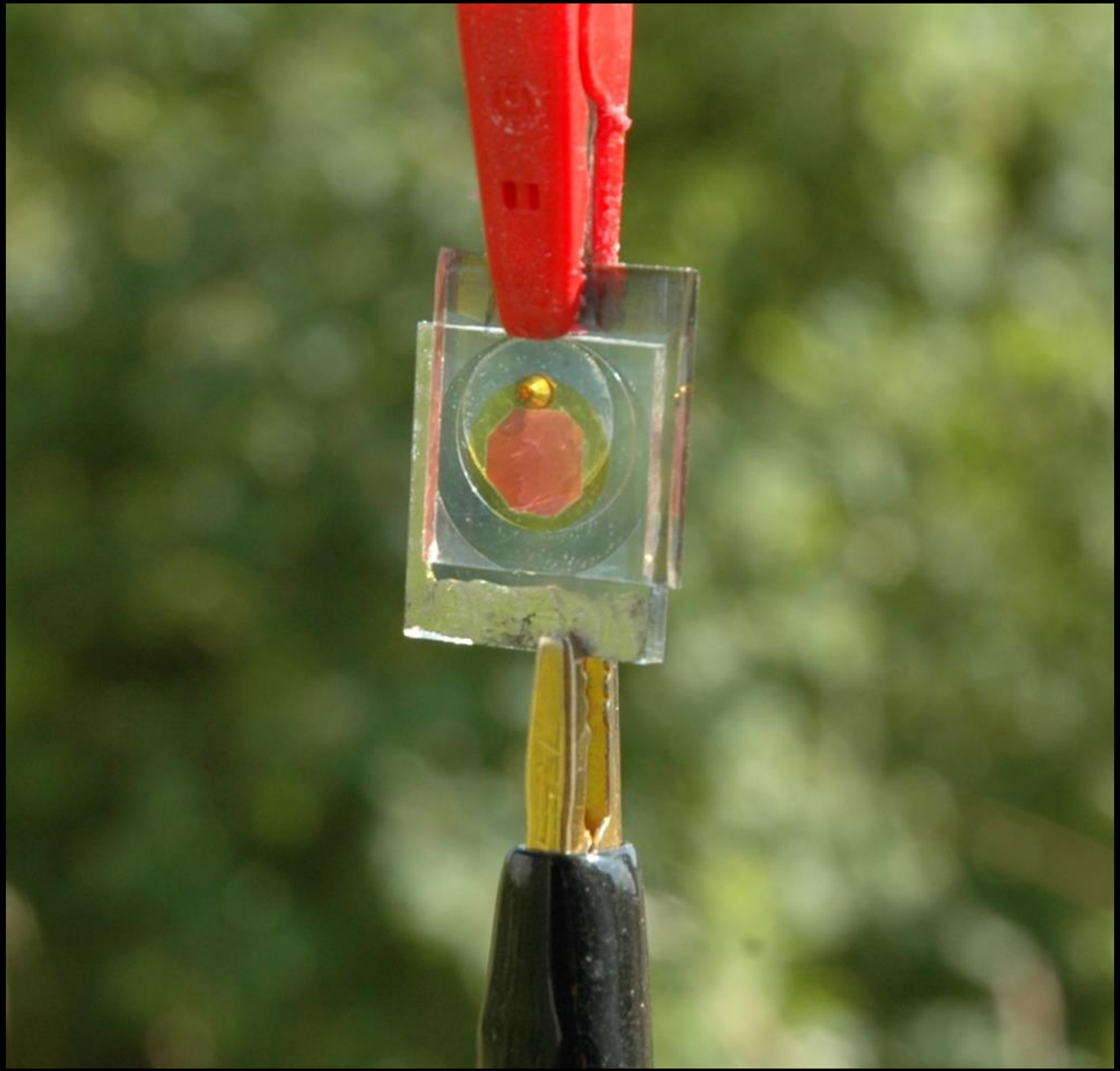
Crystalline silicon solar cell

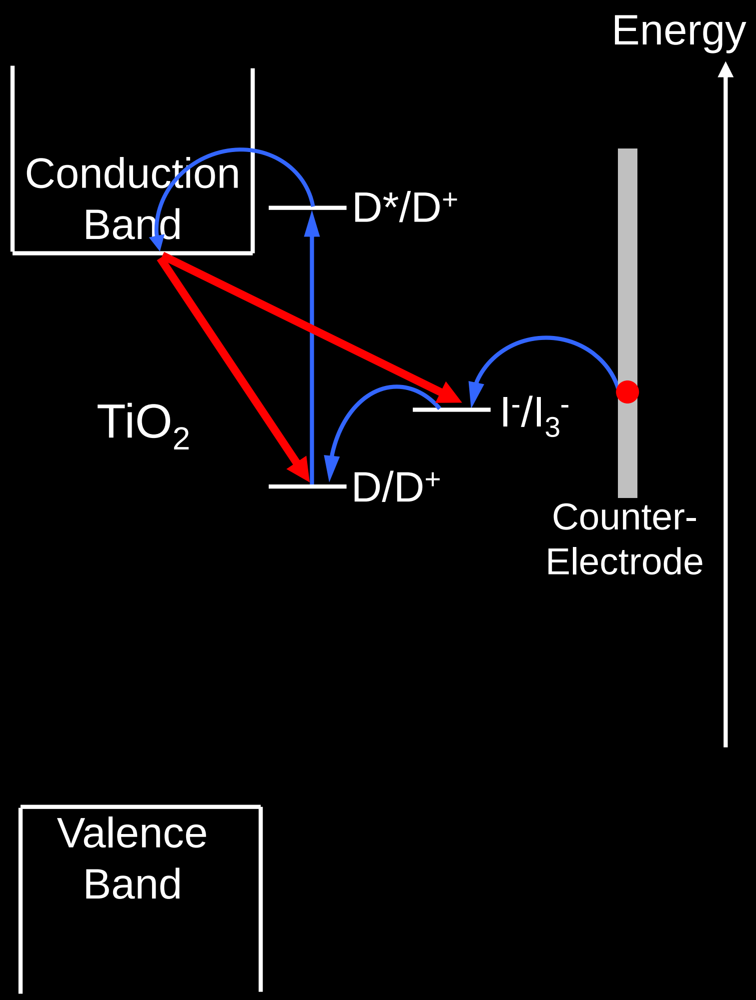




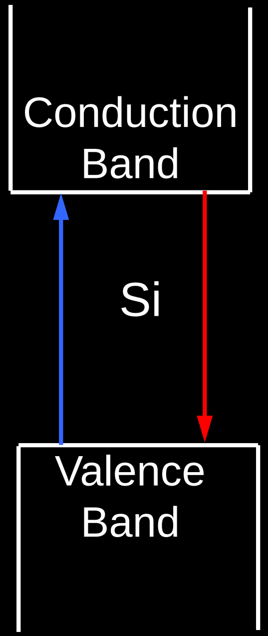


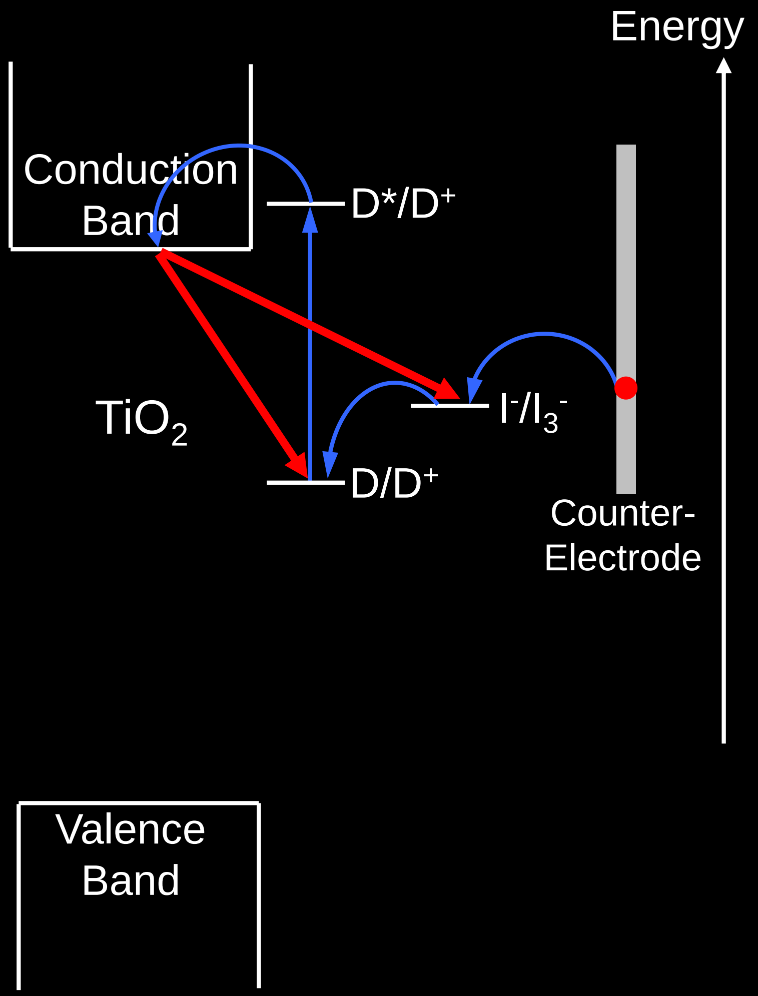
Dye-sensitized solar cell (DSSC)





Why is it Cheap?





- Silicon
  - High material purity needed to avoid recombination
- DSSC
  - Relaxed materials requirements

Perovskite pigments

Researchers tried replacing dye molecules in the DSSC with pigment particles with the perovskite structure:

Nanoscale

COMMUNICATION

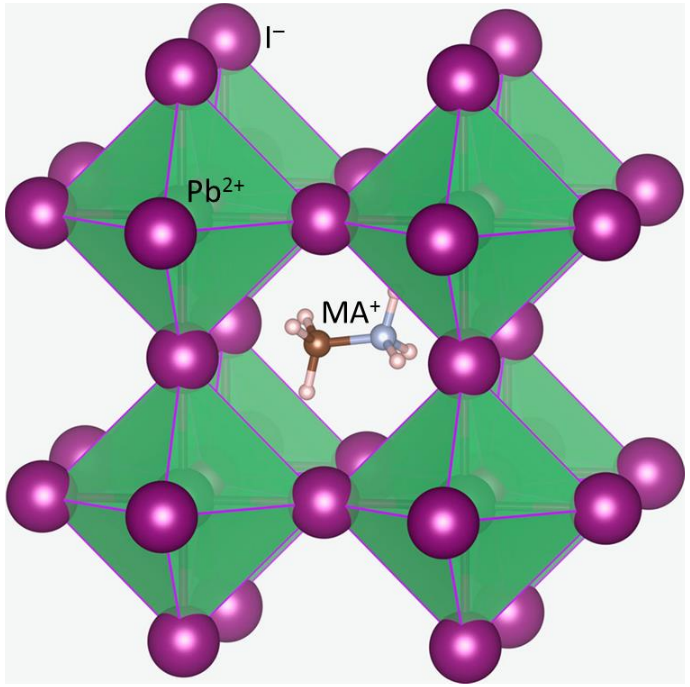
Cite this: *Nanoscale*, 2011, **3**, 4088

www.rsc.org/nanoscale

6.5% efficient perovskite quantum-dot-sensitized solar cell†

Jeong-Hyeok Im, Chang-Ryul Lee, Jin-Wook Lee, Sang-Won Park and Nam-Gyu Park*

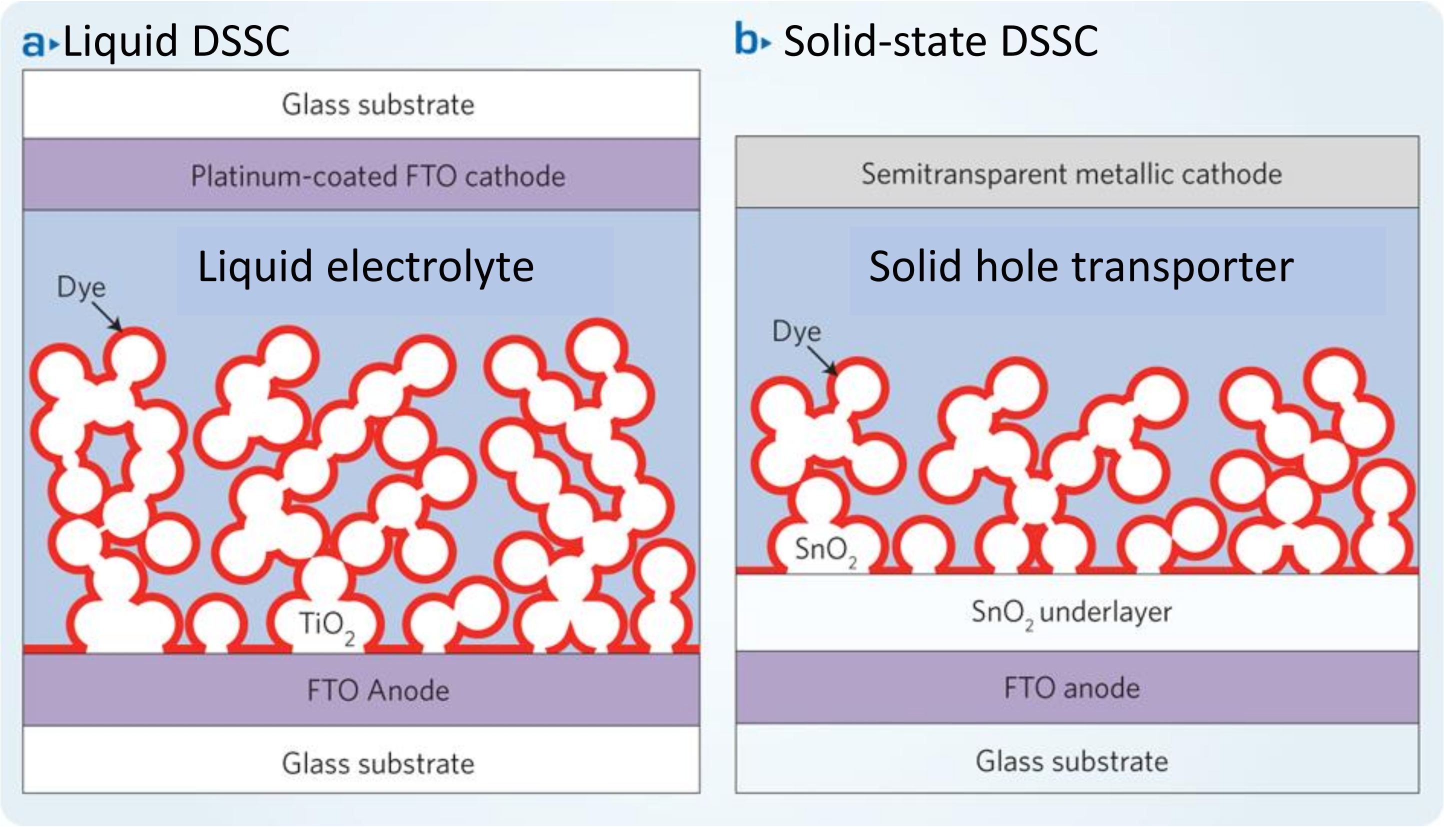
efficiency among the reported QD-sensitized solar cells. It is necessary to mention, however, that the stability of the perovskite $(CH_3NH_3)PbI_3$ QD-sensitized solar cell under continued irradiation is approximately 10 min (about 80% degradation) because QD tends to be dissolved gradually into the redox electrolyte. Studies to improve long-term stability are under way.



methylammonium (MA) lead iodide
$= CH_3NH_3PbI_3$
$= MAPbI_3$,
where $MA = CH_3NH_3^+$

Perovskite solar cell

What about perovskite pigments in the solid-state DSSC?



Perovskite breakthrough

Efficient Hybrid Solar Cells Based on Meso-Superstructured Organometal Halide Perovskites

Michael M. Lee,[1] Joël Teuscher,[1] Tsutomu Miyasaka,[2] Takurou N. Murakami,[2,3] Henry J. Snaith[1]*

The energy costs associated with separating tightly bound excitons (photoinduced electron-hole pairs) and extracting free charges from highly disordered low-mobility networks represent fundamental losses for many low-cost photovoltaic technologies. We report a low-cost, solution-processable solar cell, based on a highly crystalline perovskite absorber with intense visible to near-infrared absorptivity, that has a power conversion efficiency of 10.9% in a single-junction device under simulated full sunlight. This "meso-superstructured solar cell" exhibits exceptionally few fundamental energy losses; it can generate open-circuit photovoltages of more than 1.1 volts, despite the relatively narrow absorber band gap of 1.55 electron volts. The functionality arises from the use of mesoporous alumina as an inert scaffold that structures the absorber and forces electrons to reside in and be transported through the perovskite.

An efficient solar cell must absorb over a broad spectral range, from visible to near-infrared (near-IR) wavelengths (350 to ~950 nm), and convert the incident light effectively into charges. The charges must be collected at a high voltage with suitable current in order to do useful work (*1–8*). A simple measure of solar cell effectiveness at generating voltage is the difference in energy between the optical band gap of the absorber and the open-circuit voltage (V_{oc})

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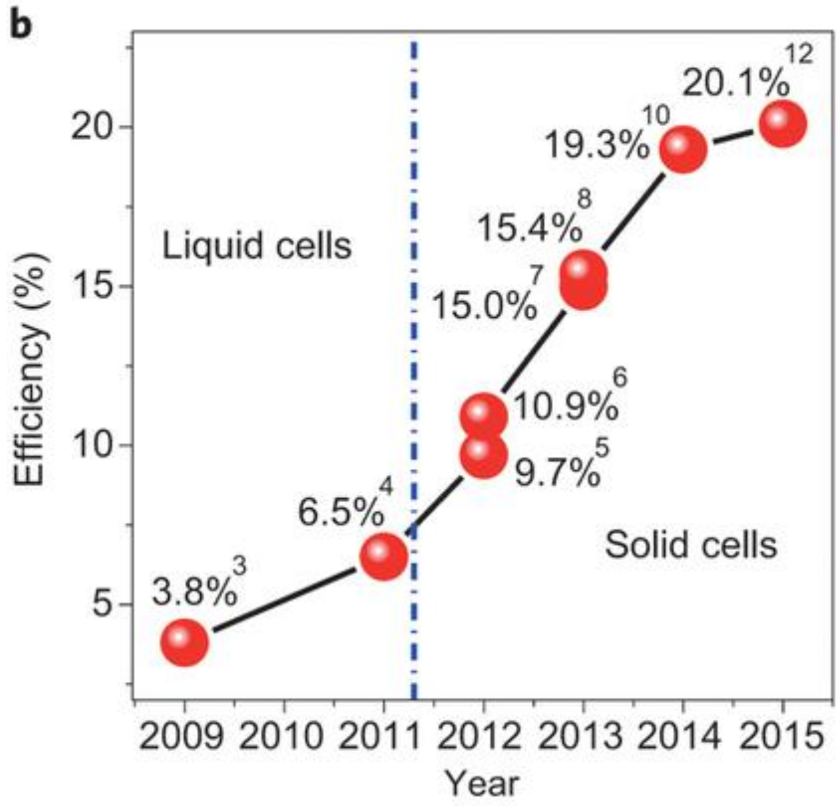
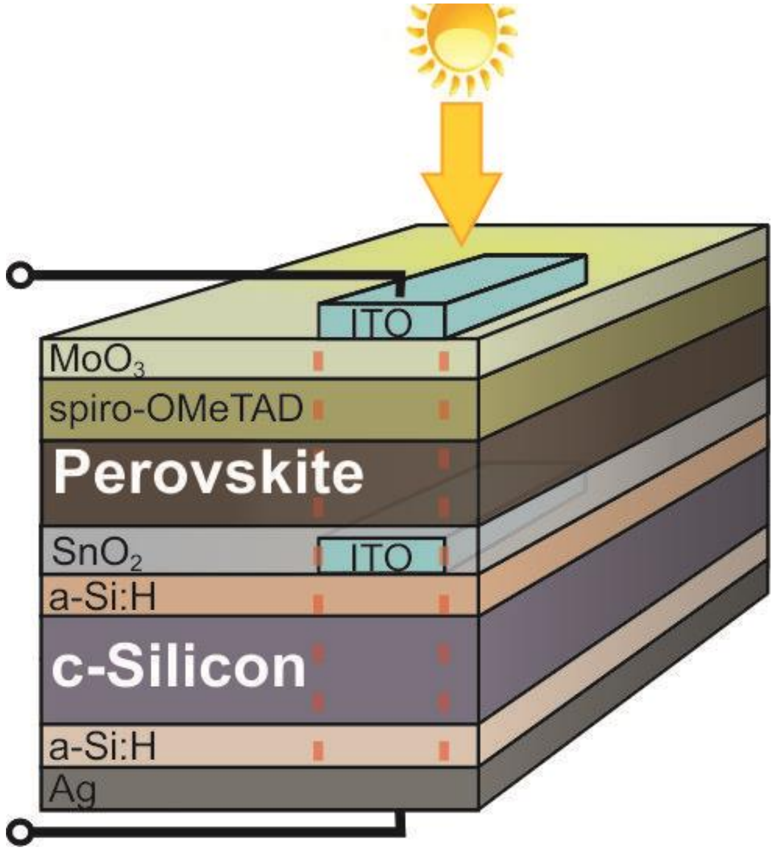
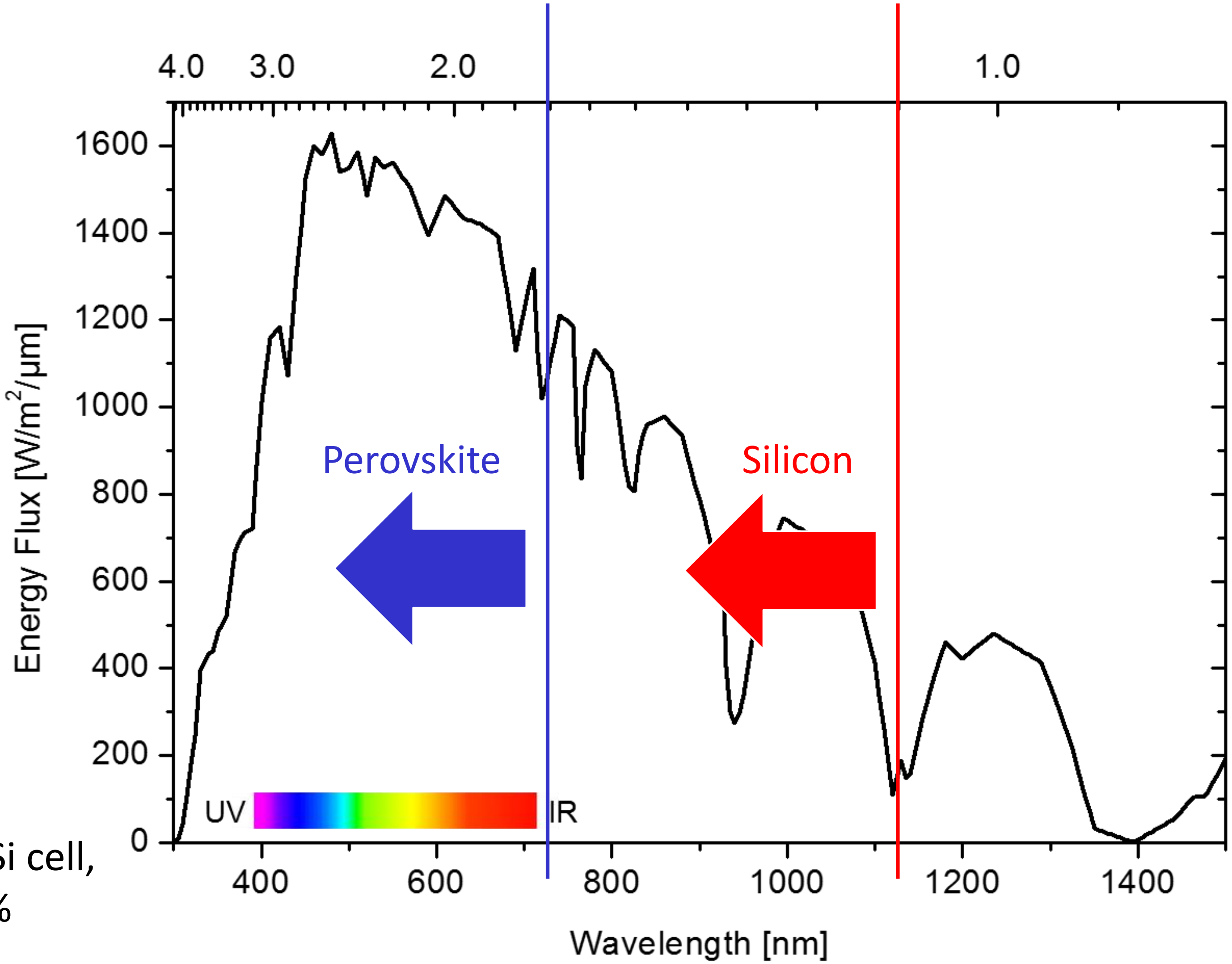
www.sciencemag.org SCIENCE VOL 338 2 NOVEMBER 2012



- *Science* named the discovery one of the Top 10 Breakthroughs of 2013
- *Nature* named Henry Snaith one of the 10 notable scientists of 2013

Potential for perovskite-silicon tandem cell





Perovskite, as a cheap layer on top of a c-Si cell, can potentially boost its efficiency to >30%

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PV Landscape as of 2017

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Crystalline Silicon (c-Si)	25.0%	26.6%
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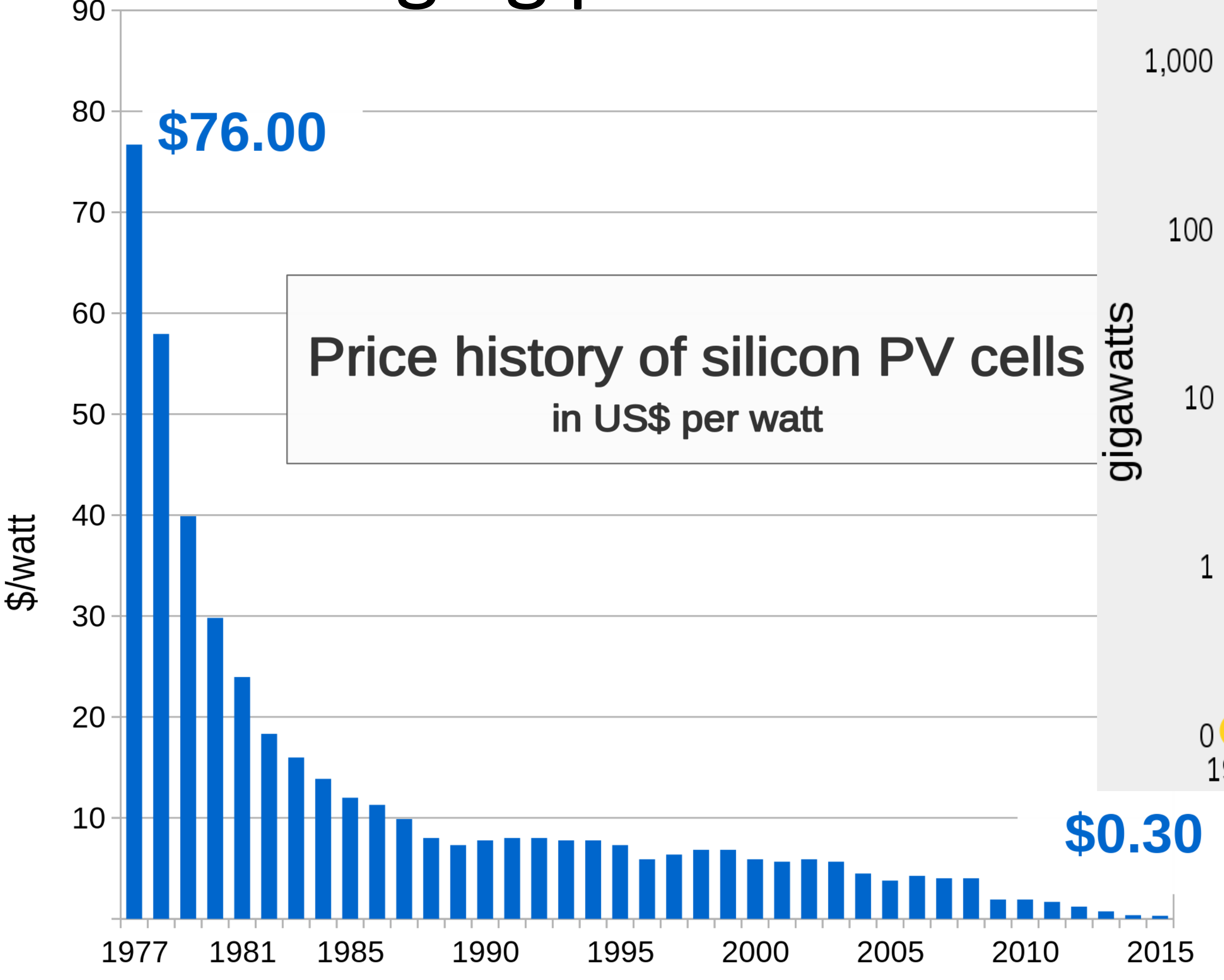
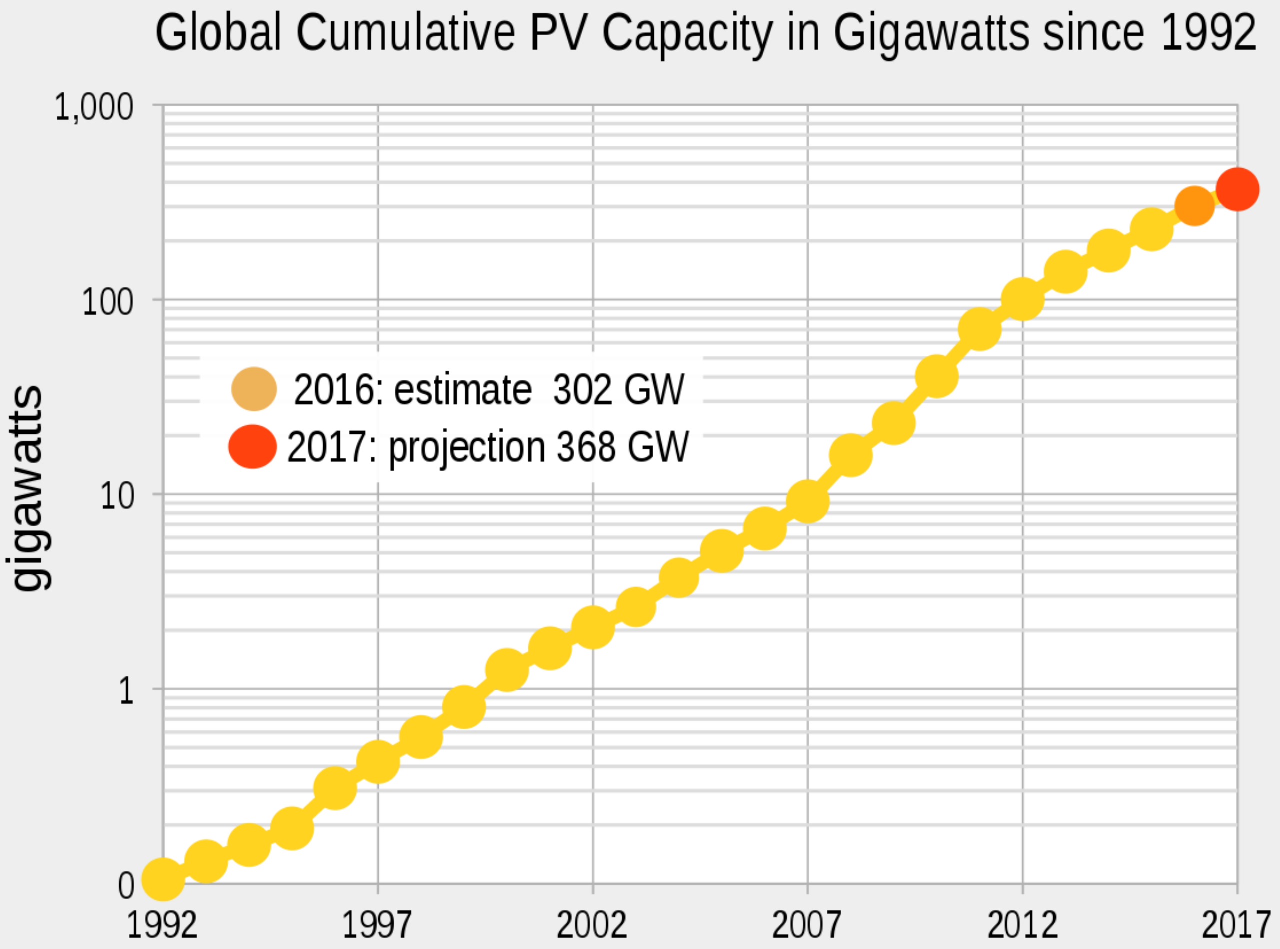
Cadmium telluride (CdTe)	16.7%	22.1%
Copper indium gallium selenide (CIGS)	20.3%	22.6%
Dye-sensitized solar cell (DSSC)	11.4%	13.0%
Perovskite		22.1%

Sources: M.A. Green et al., "Solar cell efficiency tables", *Prog. Photovolt: Res. Appl.* 25:3 (2017)
NREL "Best Research-Cell Efficiencies" chart, 14 April 2017

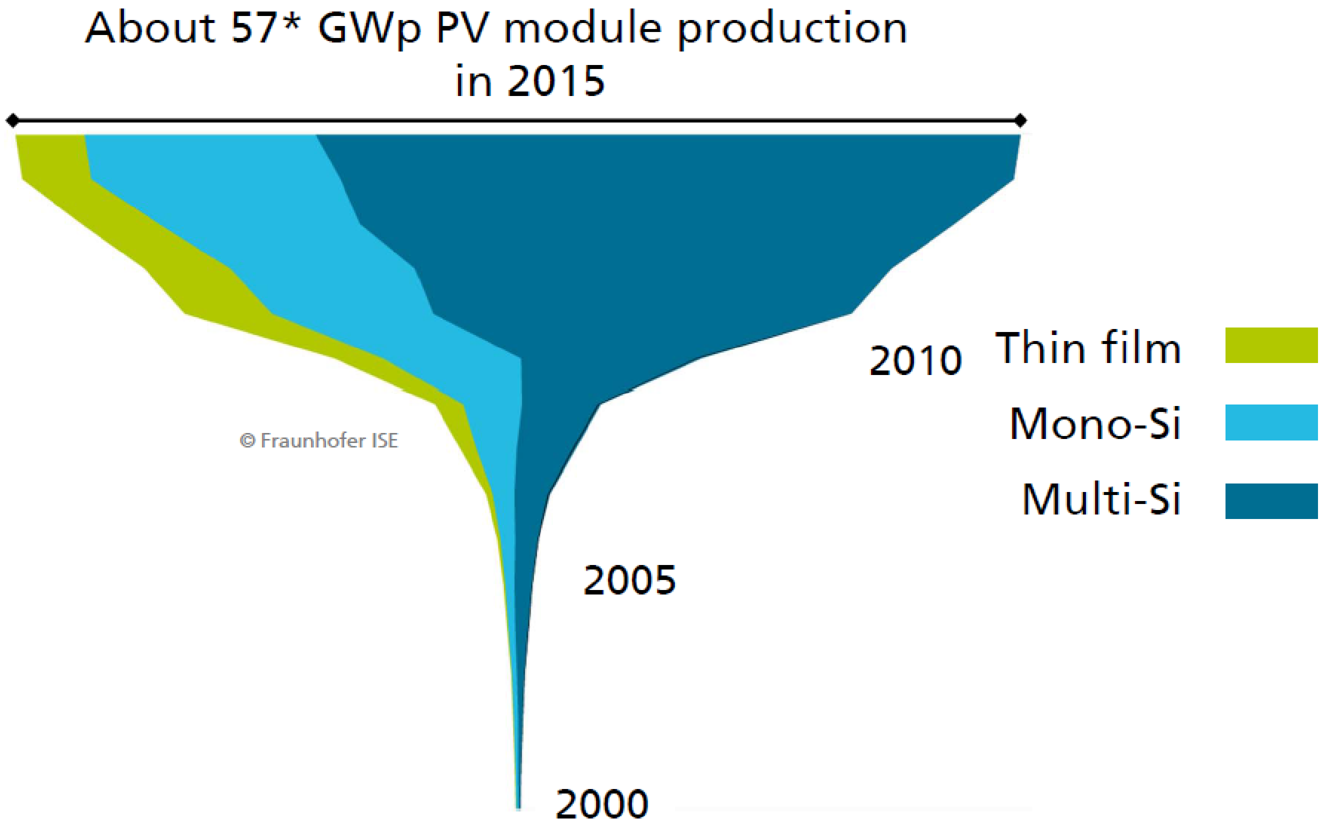
Plunging price of c-Si





Source: Bloomberg New Energy Finance & pv.energytrend.com

Today's PV market



Source: Fraunhofer ISE

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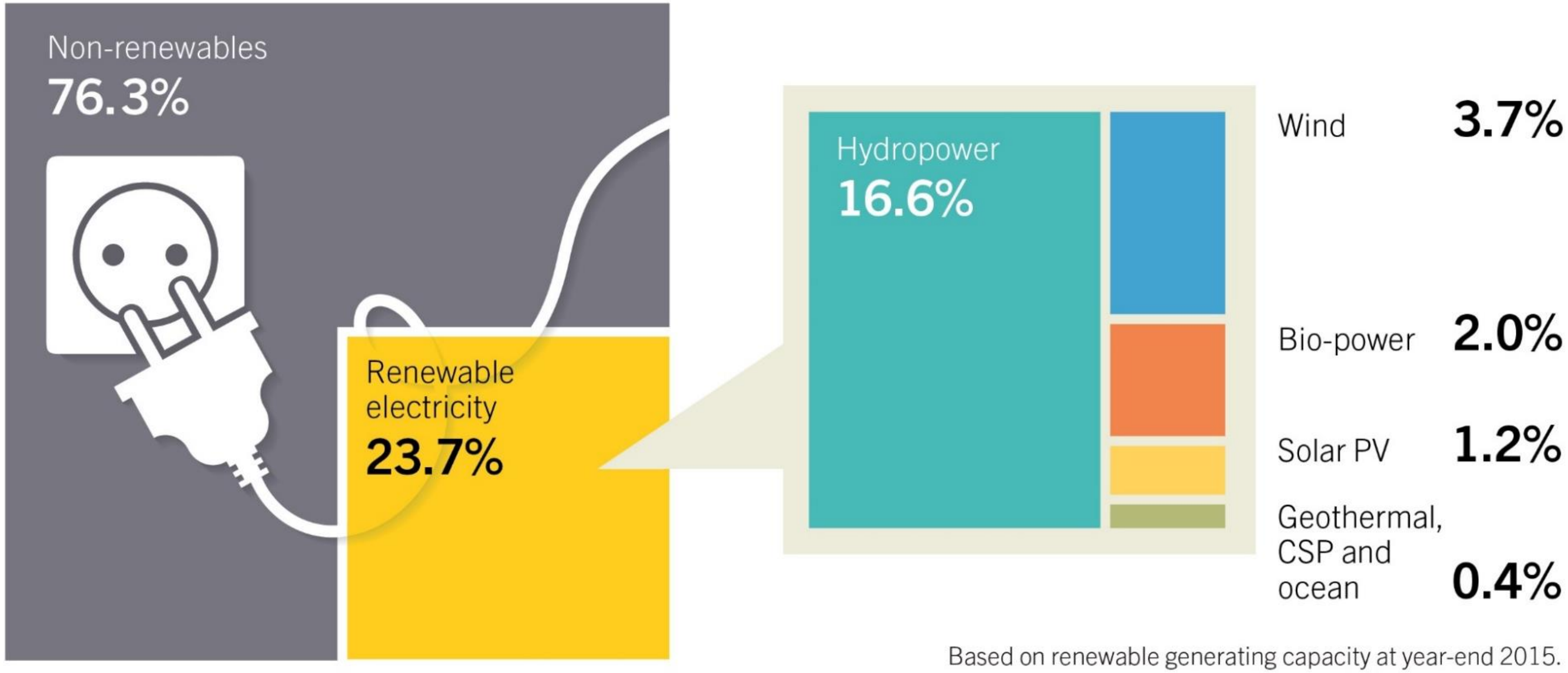
PV contribution to world energy

Estimated Renewable Energy Share of Global Electricity Production, End-2015



Based on renewable generating capacity at year-end 2015.
Percentages do not add up internally due to rounding.

REN21 Renewable Energy Policy Network for the 21st Century

REN21 *Renewables 2016 Global Status Report*

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Thanks!

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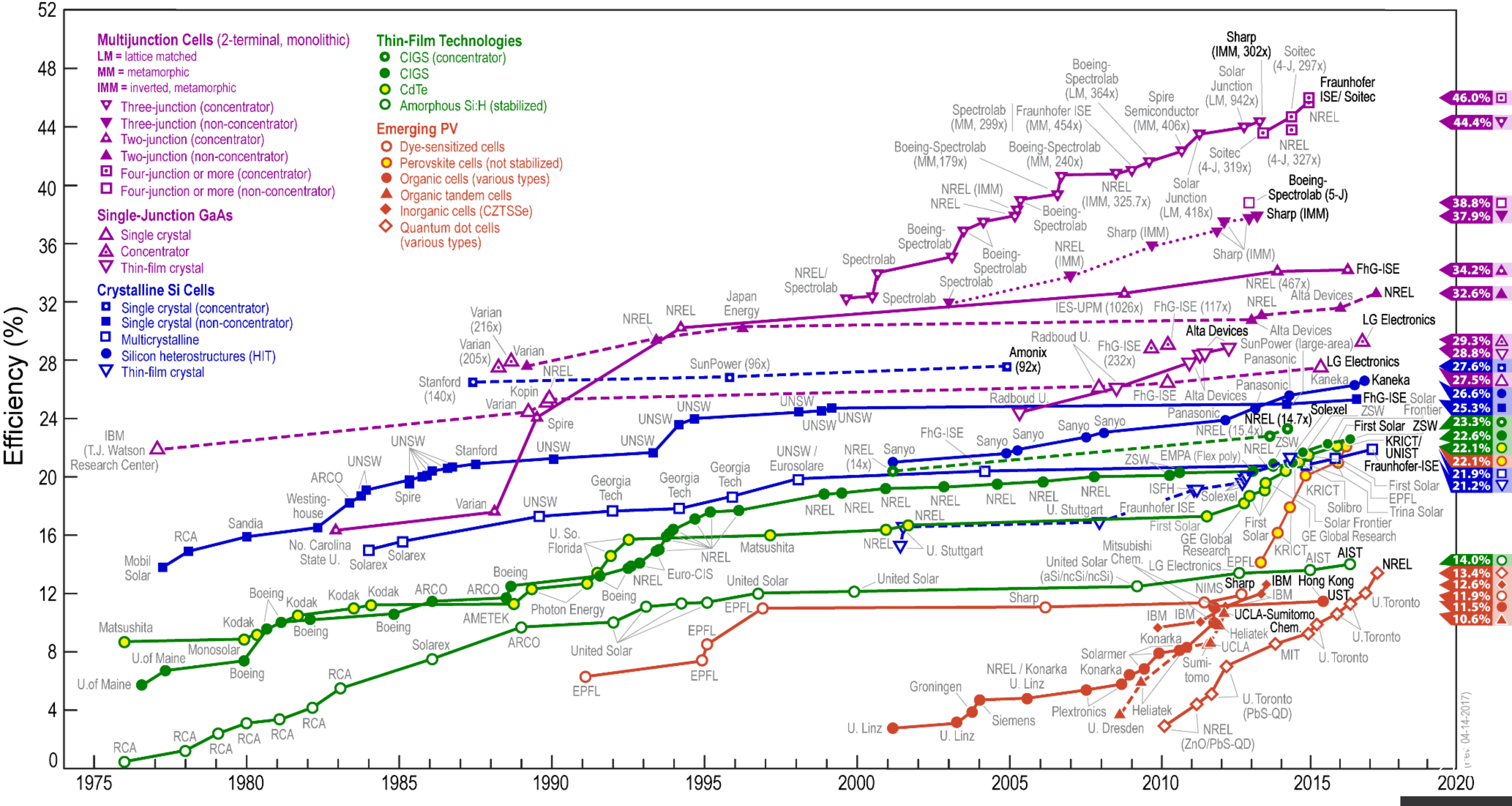
Best Research-Cell Efficiencies



"Generations" of PV technologies

Groups techs into three "generations":

- I: Si, GaAs
  - good efficiency, high cost
- II: Thin-film
  - lower efficiency, low cost
    (note that larger area is needed)
- III: The Future
  - PCE > SQ limit
  - Low cost!