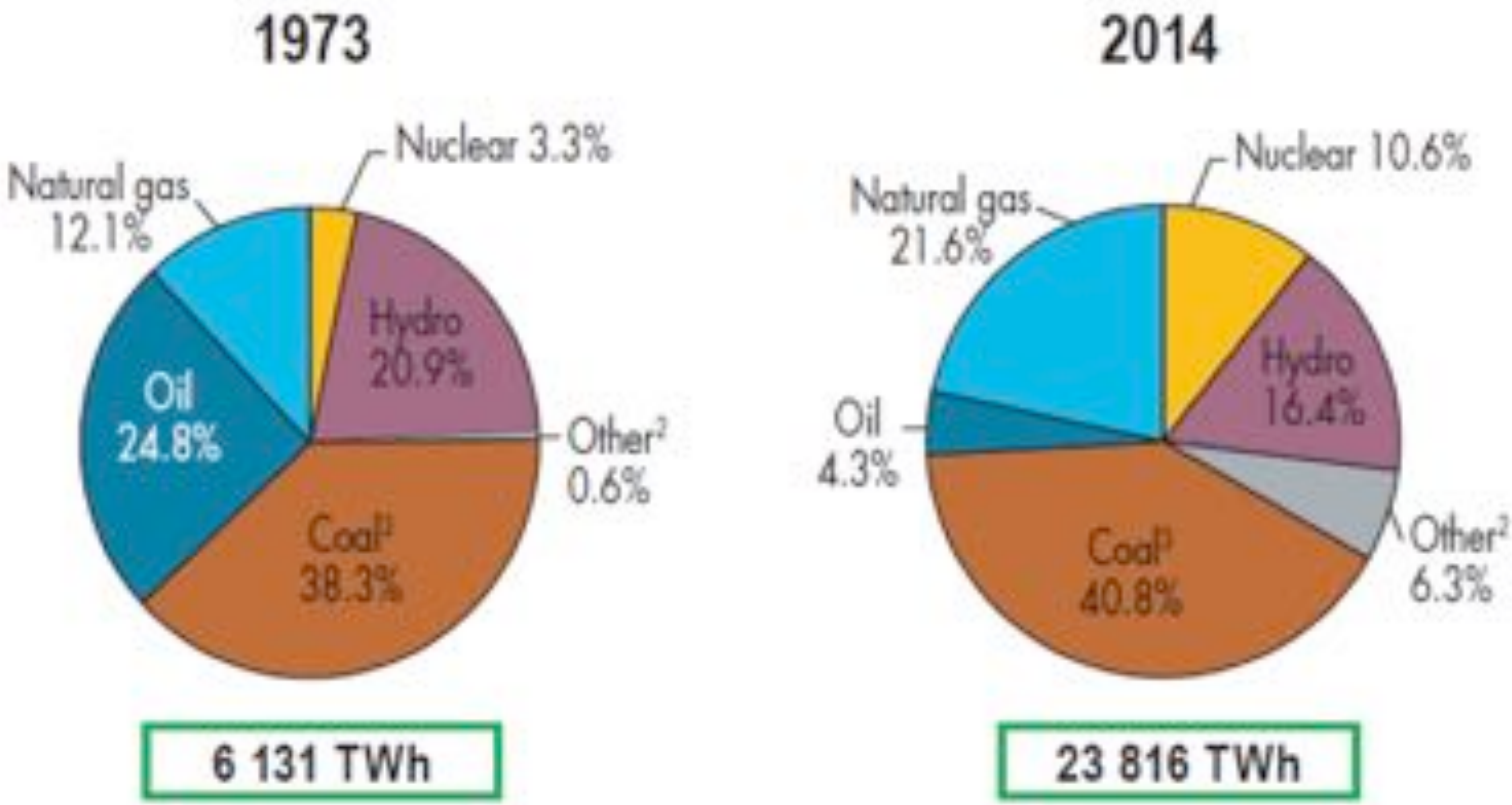
Frontiers in Solar Cells

Jian Jin

MacMillan Group Meeting

January 25, 2017

World Electricity Generation by Source

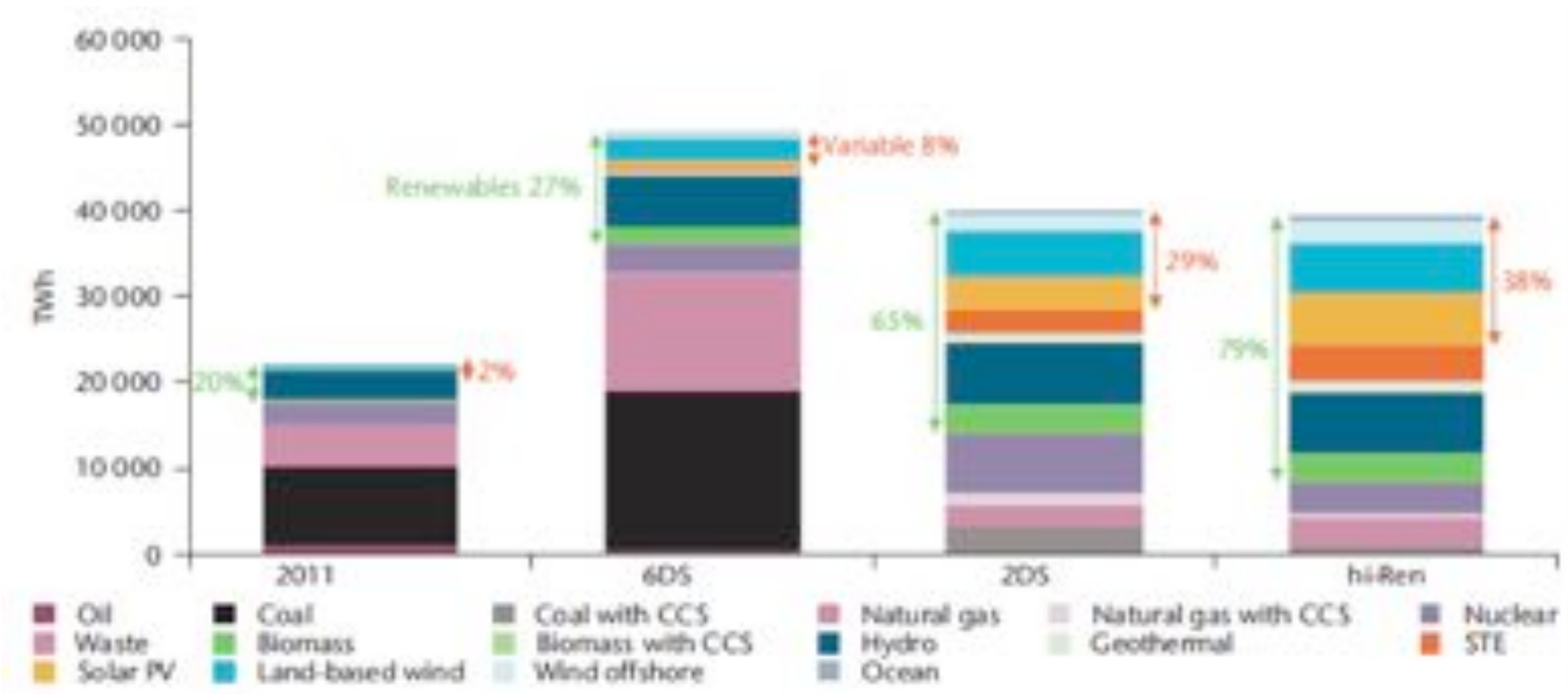


1. Excludes electricity generation from pumped storage.
2. Includes geothermal, solar, wind, heat, etc.
3. In these graphs, peat and oil shale are aggregated with coal.

International Energy Agency

Global Electricity Mix in 2011 and in 2050 (Scenario)

■ The roadmap 2014 set a goal for solar photovoltaics of 16% of total electricity generation by 2050.



International Energy Agency

Solar Energy Technologies

- Solar energy is radiant light and heat from the sun.
  - Solar fuel

    A solar fuel is a synthetic chemical fuel produced from solar energy typically by reducing protons to hydrogen, or carbon dioxide to organic compounds.

  - Artifical photosynthesis

    Artificial photosynthesis is a chemical process that replicates the natural process of photosynthesis, a process that converts sunlight, water, and carbon dioxide into carbohydrates and oxygen.

  - Energy storage
  - Solar architecture
  - Greenhouse

Solar Energy Technologies

- Solar energy is radiant light and heat from the sun.
  - Solar thermal energy: Concentrated solar power

Concentrating Solar Power (CSP) systems use lenses or mirrors and tracking systems to focus a large area of sunlight into a small beam. The concentrated heat is then used as a heat source for a conventional power plant.

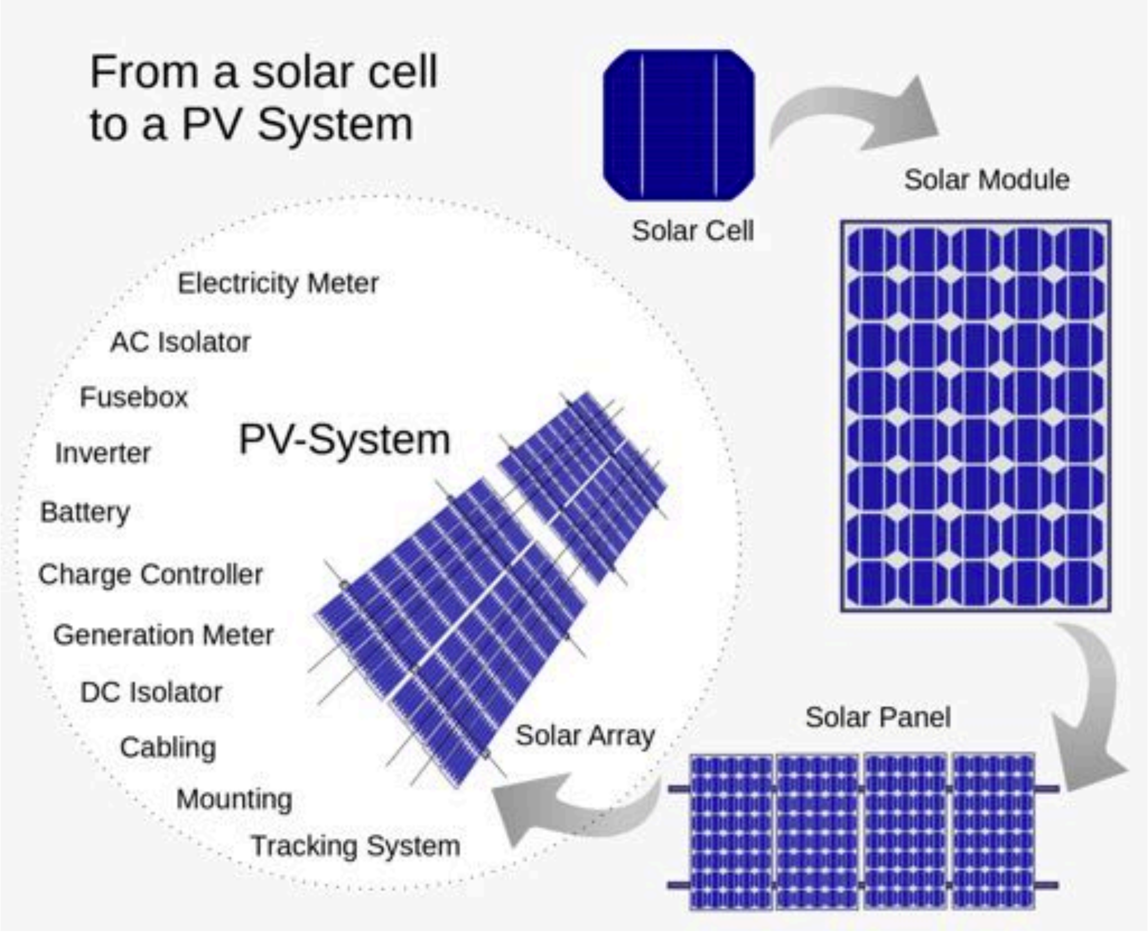
SolarReserves Crescent Dunes CSP Project, near Tonopah, Nevada, has an electricity generating capacity of 110 megawatts.

Solar Energy Technologies

■ Solar energy is radiant light and heat from the sun.

■ Photovoltaics: Solar Cell

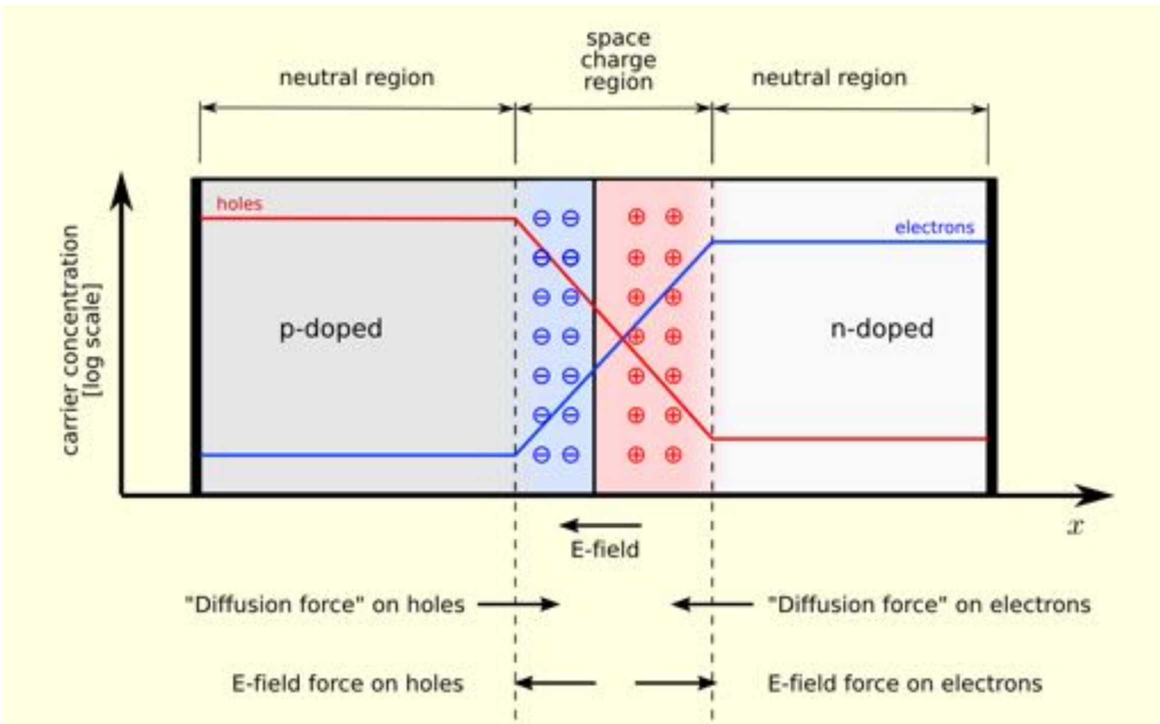
An electrical device that converts the energy of light directly into electricity by the photovoltaic effect, which is a physical and chemical phenomenon.



Theory

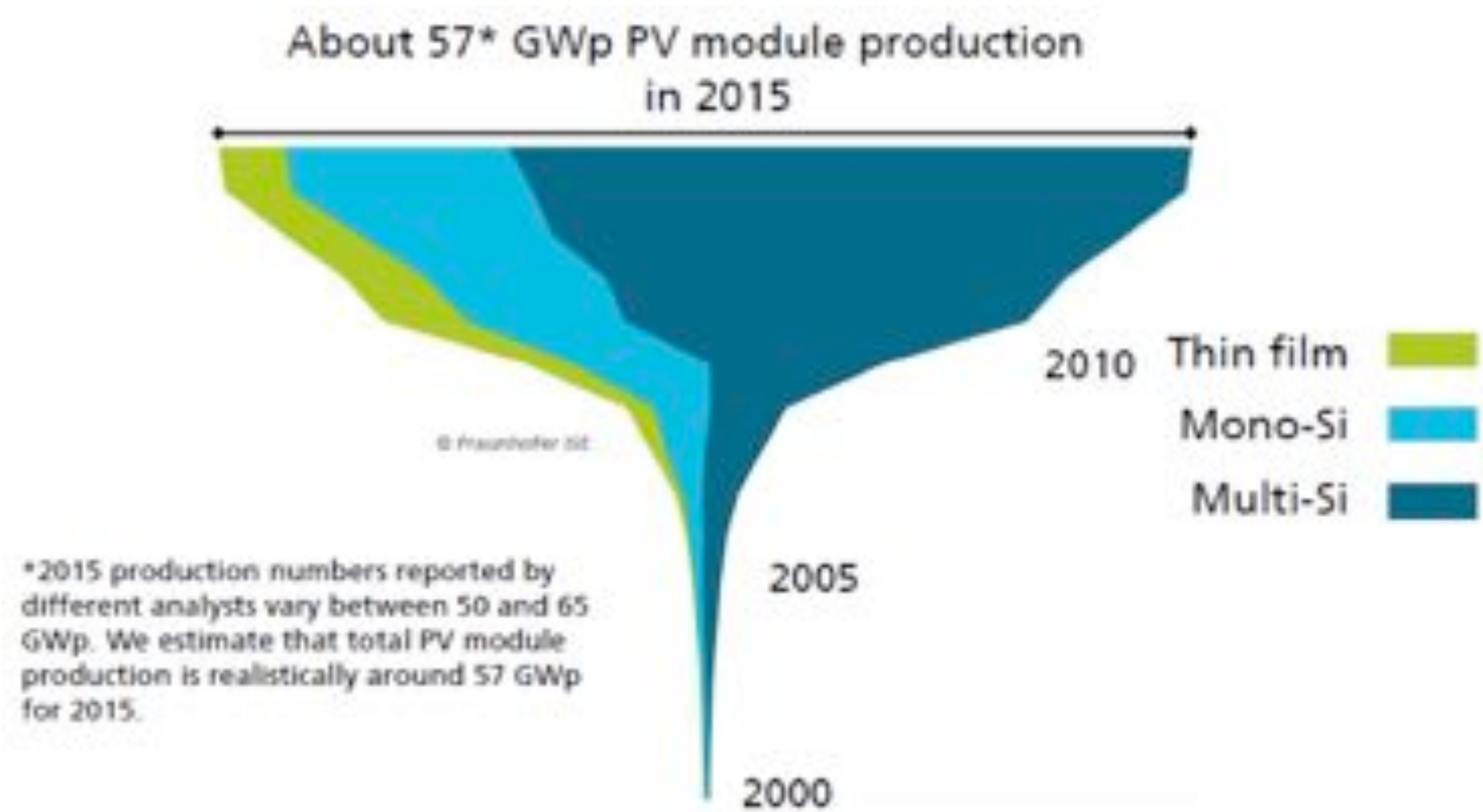
- The operation of a photovoltaic cell requires three basic attributes
  - The absorption of light, generating either electron-hole pair or excitons.
  - The separation of charge carriers of opposite types.
  - The separate extraction of those carriers to an external circuit.
- Separation mechanism: p-n junction
  - A p–n junction is a boundary or interface between two types of semiconductor material, p-type and n-type.
  - A common dopant for p-type silicon is boron.
  - A common dopant for n-type silicon is phosphorus.

cathode+



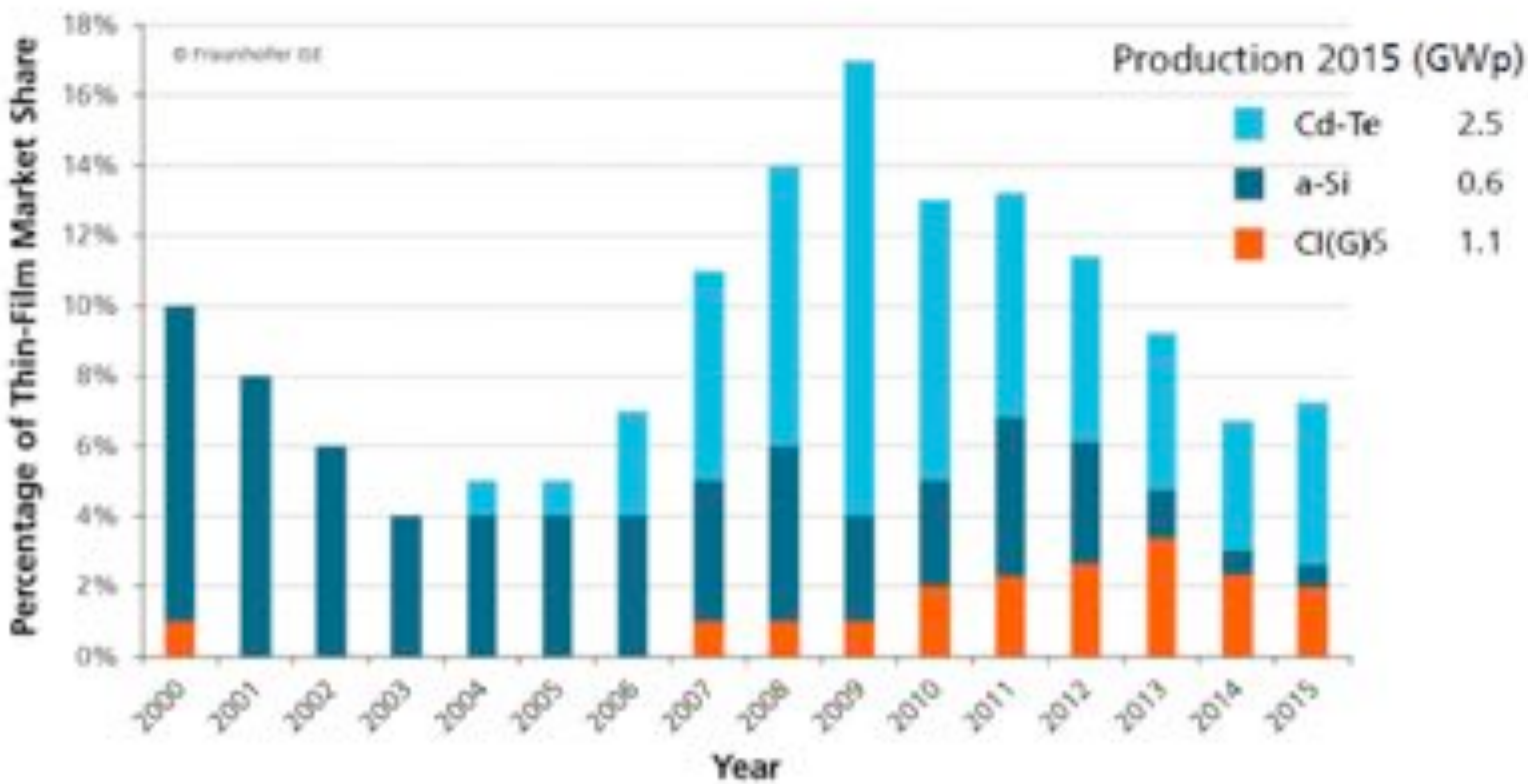
-anode

Worldwide Annual PV Production by Technology



Fraunhofer ISE

Market Share of Thin-Film Technologies



Fraunhofer
ISE

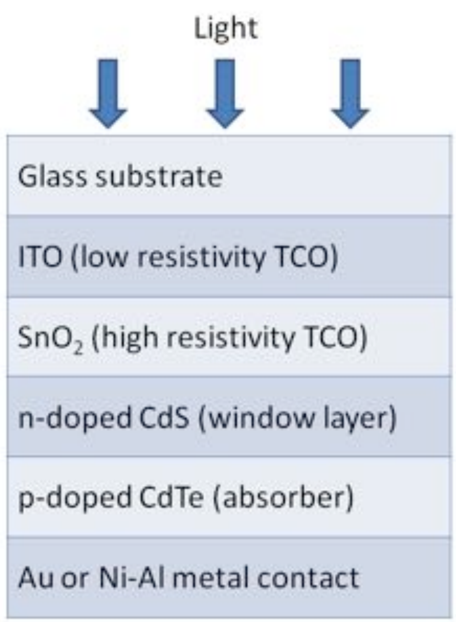
Crystalline Silicon Solar Cells

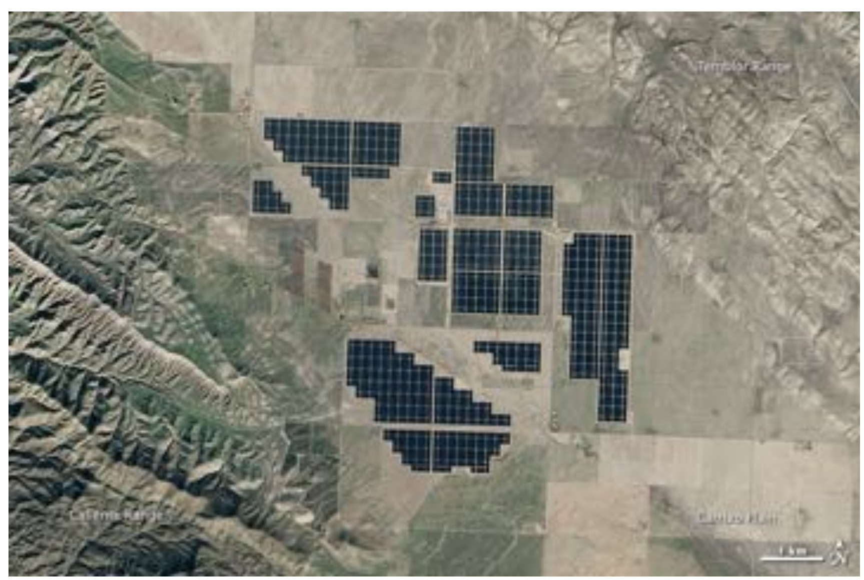
- Monocrystalline silicon
  - Grown by the Czochralski process into cylindrical ingots of up to 2 meter in length
  - Sliced into thin wafers between 160 - 200 μm thick
  - Cut into an octagon shape
  - More expensive than most other types of cells
  - More efficient, with a record lab cell efficiency: 25.3%
- Multicrystalline silicon
  - Made from cast square ingots - large blocks of molten silicon carefully cooled and solidified
  - Less expensive, but also less efficient, than monocrystalline silicon
  - The most common type of solar cells, with a record lab cell efficiency: 21.3%

Thin Film Solar Cells

- Amorphous silicon
  - Made of non-crystalline silicon
  - The most well-developed thin film technology to-date
  - Deposit a very thin silicon layer of only 1 - 2 μm on glass, plastic or metal
  - Absorbs visible light more strongly than the higher power density infrared light
  - Less expensive but less efficient, with a record lab cell efficiency: 14.0%

- Cadmium telluride
  - The only thin film material so far to rival crystalline silicon in cost/watt
  - Cadmium is highly toxic and tellurium supplies are limited
  - Record lab cell efficiency: 22.1%



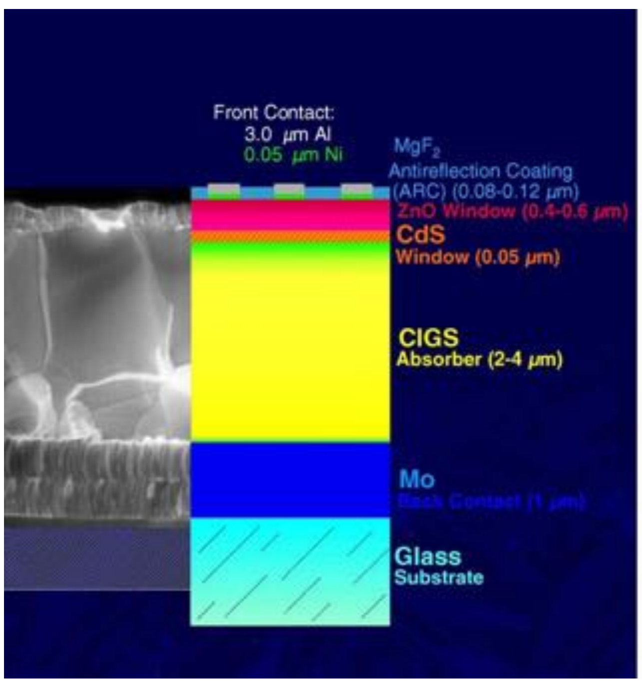


The Topaz Solar Farm, world's largest PV power station in 2014

Thin Film Solar Cells

- Copper Indium Gallium Selenide
  - Deposit a thin layer of $CuIn_xGa_{(1-x)}Se_2$ on glass or plastic.
  - CIGS is mainly used in the form of polycrystalline thin films
  - The best efficiency achieved: 22.6%

- Gallium Arsenide
  - Single-crystalline thin film solar cells
  - Very expensive, hold the world's record in efficiency for single-junction solar cell at 28.8%
  - Commonly used in multijunction solar cells for concentrated photovoltaics
  - Used for solar panels on spacecrafts



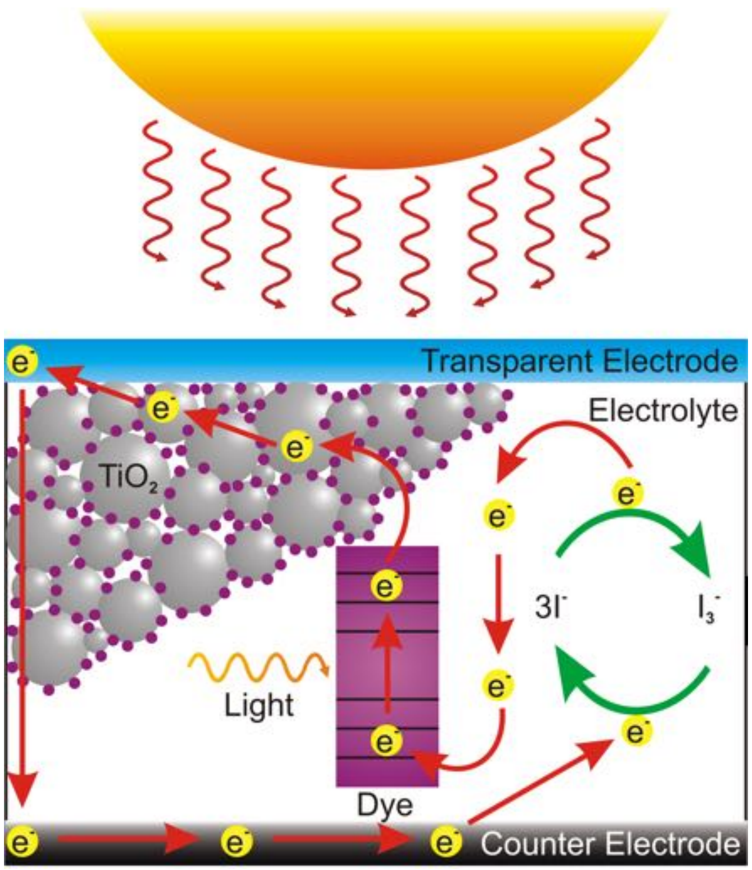
Triple-junction GaAs cells covering MidSTAR-1

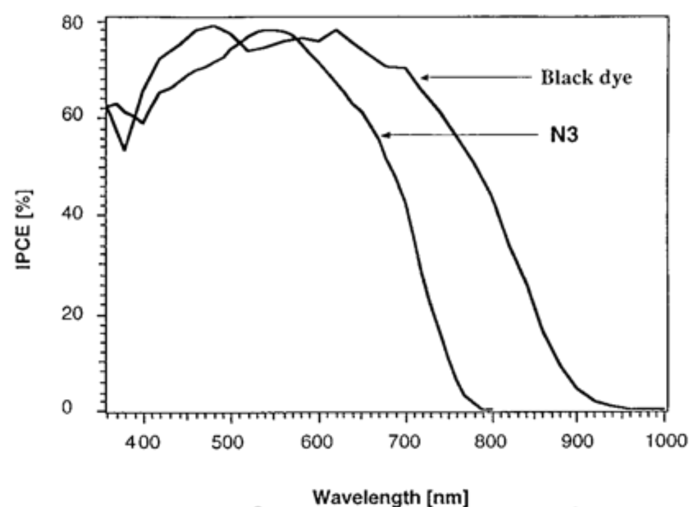
Dye-sensitized Solar Cells

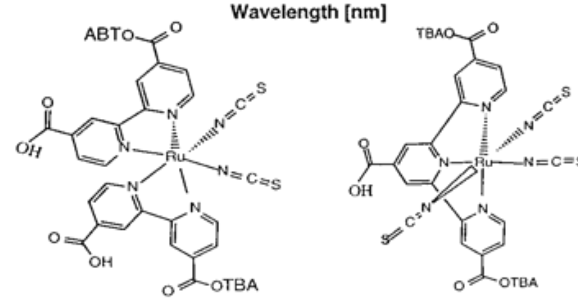
- 1968, Helmut Tributsch, illuminated chlorophyll could generate electricity at oxide electrodes.

- 1988, Brian O'Regan and Michael Gratzel co-invented the modern version of a dye solar cell with the trimeric ruthenium complex, $Ru(H_2dcbpy)_2[Ru(bpy)'_2(CN)_2]_2$, 7.1% efficiency. [Nature]

- 1993, Michael Gratzel discovered N_3; 1997, black dye, 10.4% efficiency.







N3

Black dye

Dye-sensitized Solar Cells

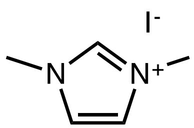
- 2003, Micheal Gratzel, a quasi-solid-state polymer gel electrolyte, 6.1% efficiency. [Nature Materials]

3-methoxypropionitrile + polyvinylidenefluoride-co-hexafluoropropylene

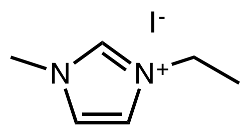
dye Z907: cis-Ru(H2dcbpy)(dnbpy)$(NCS)_2$

- 2008, Micheal Gratzel, a new solvent-free liquid redox electrlyte consisting of a melt of 3 salts, 8.2% efficiency. [Nature Materials]

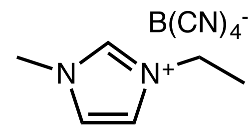
DMII/EMII/EMITCB



1,3-dimethylimidazolium iodide



1-ethyl-3-methylimidazolium iodide



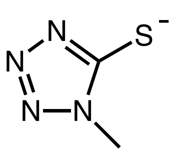
1-ethyl-3-methylimidazolium $B(CN)_4$

- 2009, Michael Gratzel + Benoit Marsan claimed to have overcome two of DSC's major issues:
  - At the cathode, platinum was replaced by CoS, 6.5% efficiency. [JACS]

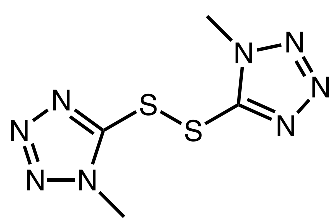
far less expensive, more efficient, more stable and easier to produce

  - New molecules for the electrolyte, transparent, non-corrosive, 6.4% efficiency. [Nature Chem]

increase the photovoltage and improve the cell's output and stability



T^-



T_2 vs I^- I_2

Dye-sensitized Solar Cells

- 2012, Northwestern University, Mercouri Kanatzidis, solid hole conductor, 10.2% efficency. [Nature]

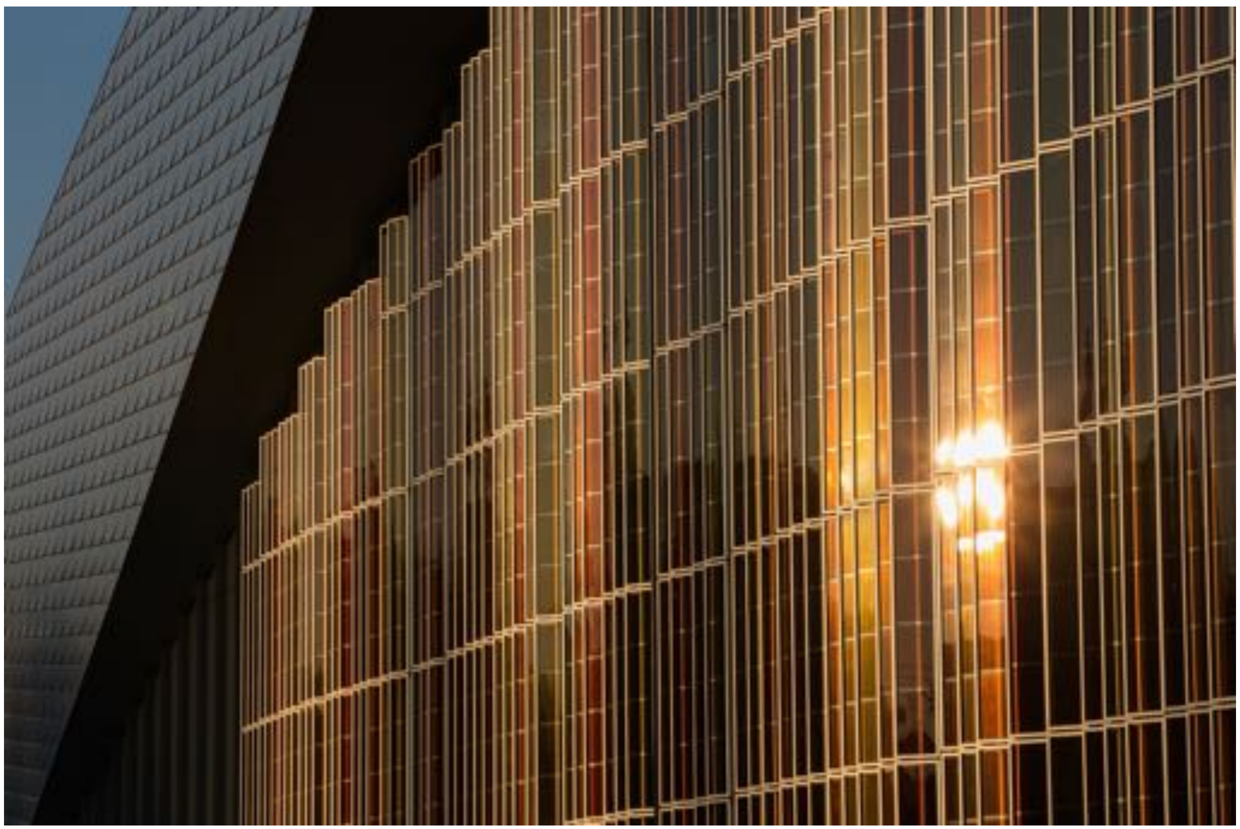
solid $CsSnI_3$, doped with SnF_2, p-type

dye N719

nanoporous TiO_2

- 2014, EPFL's new convention center integrated with DSSC.

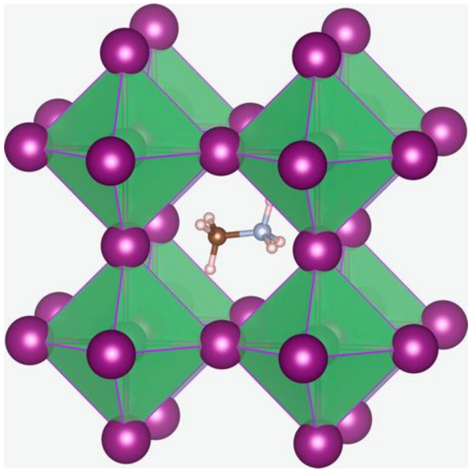
300 m^2, 1400 modules of 50 cm * 35 cm



Perovskite Solar Cells

- Perovskite: a calcium titanium oxide mineral, calcium titanate $CaTiO_3$.

- Perovskite structure: cystal structure ABX_3 as $CaTiO_3$.



- $CH_3NH_3PbI_3$, known compound, new application

new type of solar cells was born!

Perovskite Solar Cells

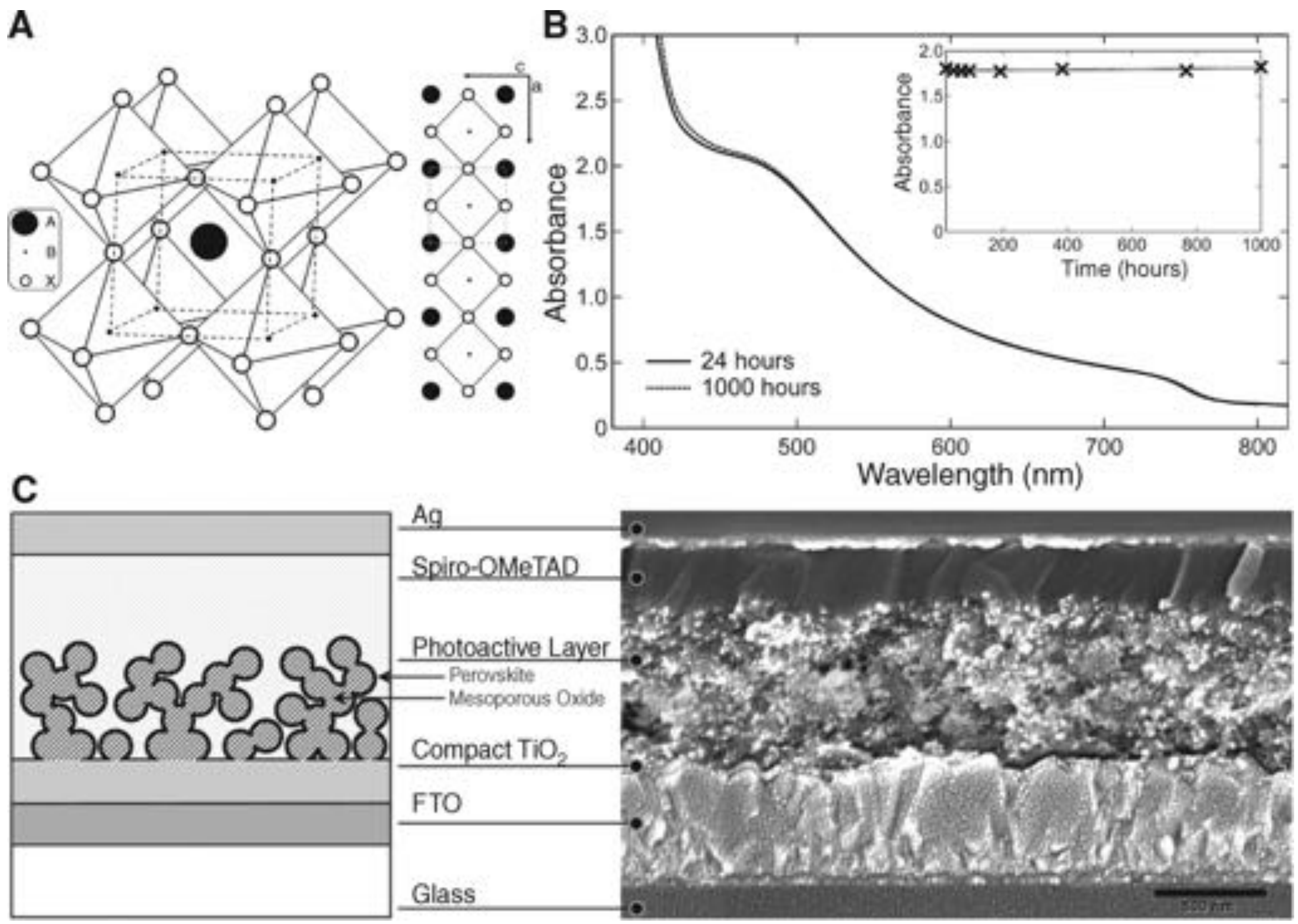
- 2009, The Univeristy of Tokyo, Tsutomu Miyasaka, 3.8% efficency. [JACS]

based on a dye-sensitizer solar cell arcitecture

$CH_3NH_3PdI_3$ as the sensitizer

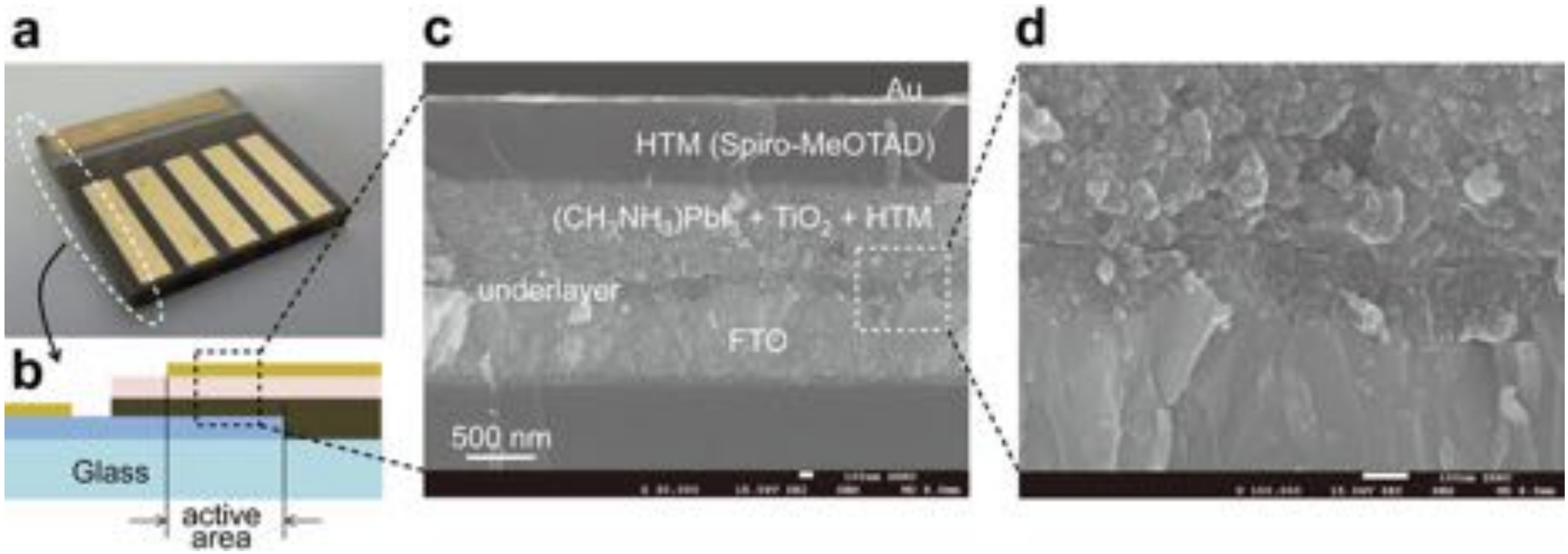
LiI/I_2 in methoxyacetonitrile as the electrolyte

- 2012, University of Oxford, Henry Snaith, solid hole conductor, 10.9% efficiency. [Science]



Perovskite Solar Cells

- 2012, Nam-Gyu Park, Michael Gratzel, spiro-MeOTAD, $CH_3NH_3PbI_3$, 9.7% efficiency. [Scientific Reports]



- 2013, Michael Gratzel, a sequential deposition technique, 15% efficiency. [Nature]

- 2013, Michael Gratzel, a thermal vapour deposition technique, 15% efficiency. [Nature]

Perovskite Solar Cells

- 2014, Oxford, Henry Snaith, determined electron-hole diffusion length. [Science]

  >1 μm for $CH_3NH_3PbI_{3-x}Cl_x$ ~0.1 μm for $CH_3NH_3PbI_3$

- 2014, UCLA, Yang Yang, interface engineering, 19.3% efficiency.

- 2015, Michael Gratzel, 21.0% efficiency.

- 2016, KRICT and UNIST, 22.1% efficiency.

2009 - 2016, 3.8% - 22.1% !

The IV-curves of perovskite solar cells show a hysteretic behavior, which yield ambiguous efficiency values.

Only a small fraction of publications acknowledge the hysteretic behavior of the described devices, even fewer articles show slow non-hysteretic IV curves or stabilized power outputs.

- Stability

  One big challenge for perovskite solar cells (PSCs) is the aspect of short-term and long-term stability.

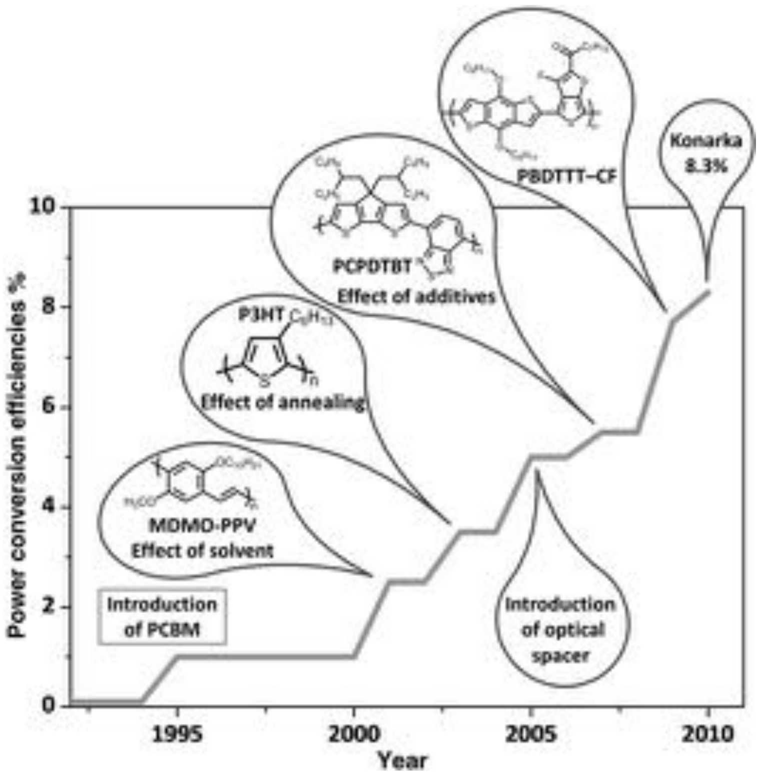
  - Environment influence (moisture and oxygen)

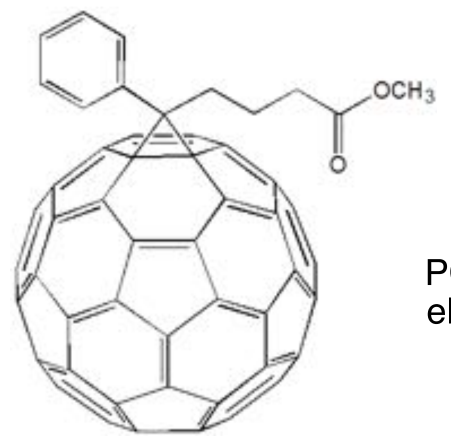
  - Thermal influence (temperature and intrinsic heating under applied voltage)

  - Photo influence (UV light)

Organic Solar Cells

- Organic (polymer) solar cell is a type of photovoltaic made with organic molecules including polymers.





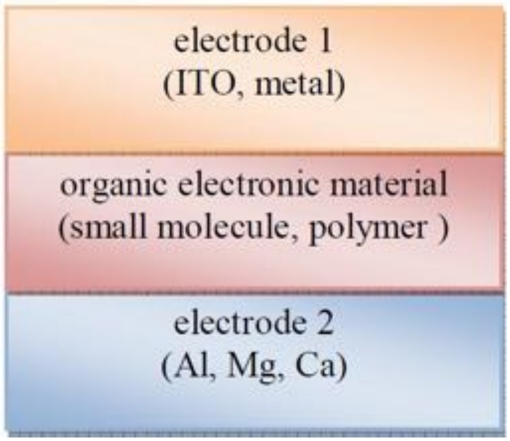
PCBM
electron acceptor

- Advantages
  - solution-processable at high throughput
  - cheap
  - good flexibility
  - molecular engeering can change the band gap
  - high absorption of light, 0.1 μm thin film

- Drawbacks
  - low efficiency, record 11.7%
  - low stability
  - low strength

Organic Solar Cells

Single layer organic solar cells



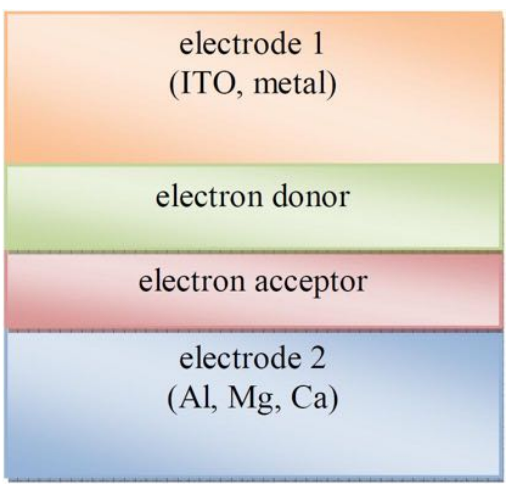
a layer of indium tin oxide with high work function

these two layers set up an electric field in the organic layer

a layer of Al, Mg or Ca with low work function

week electric field, low efficiency

Bilayer organic solar cells



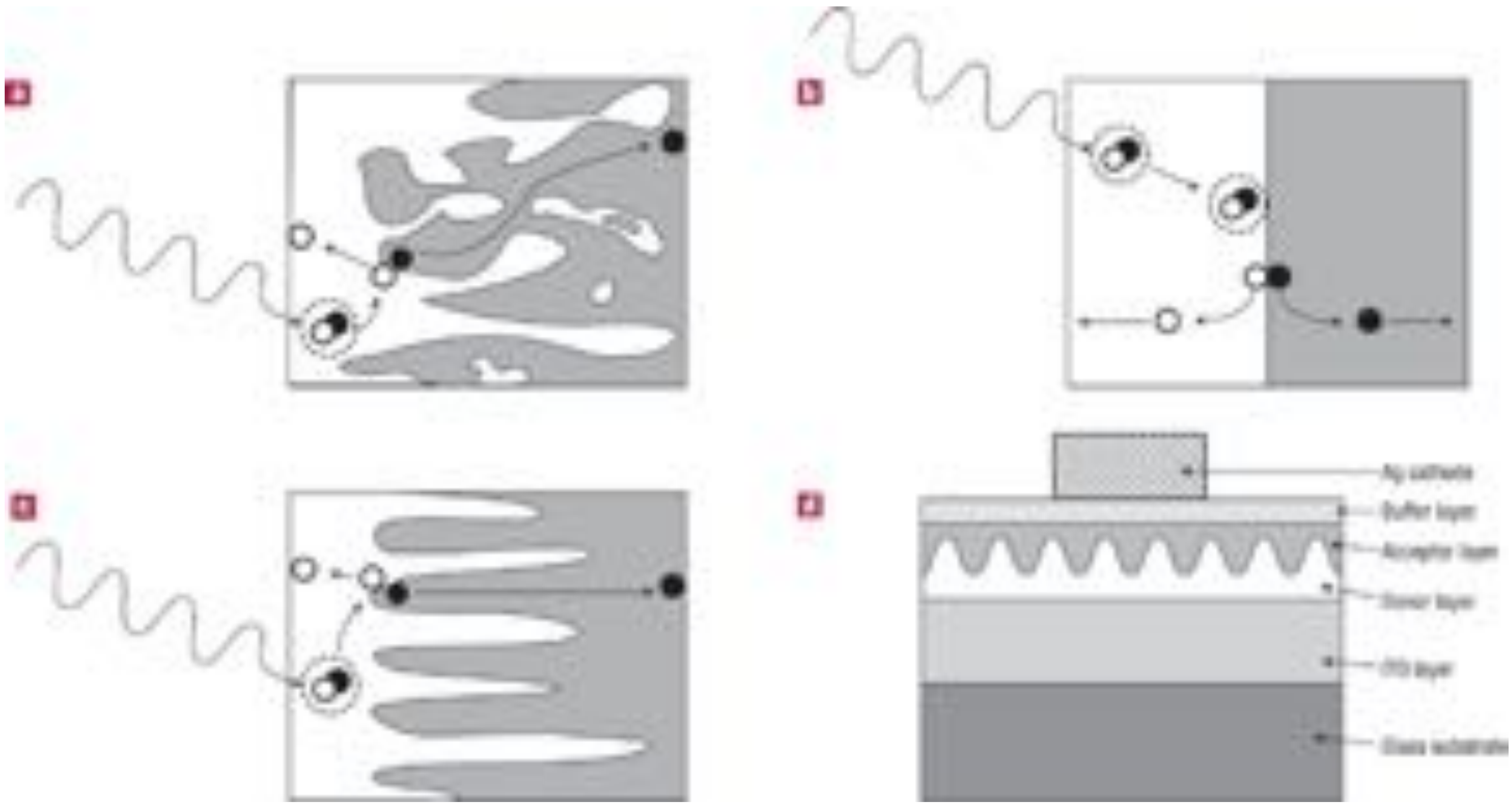
lower electron affinity and ionization potential, copper phthalocyanine

higher electron affinity and ionization potential, C60, PCBM, perylene

diffusion length of excitons is around 10 nm
a polymer layer needs a thickness of 100 nm to absorb enough light

Organic Solar Cells

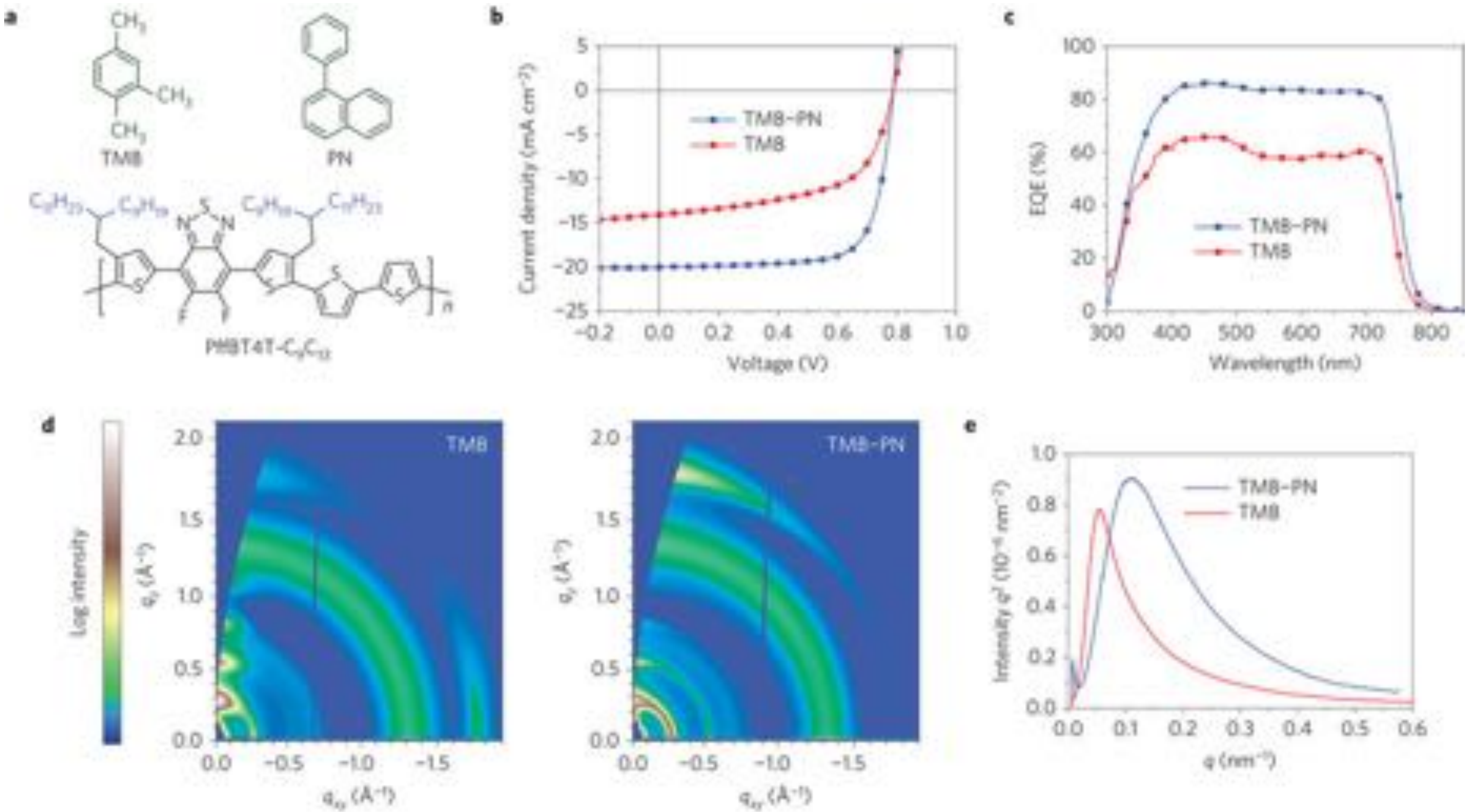
- Controled growth heterojunction, 2005, Princeton University, Stephen Forrest. [Nature Materials]



Organic Solar Cells

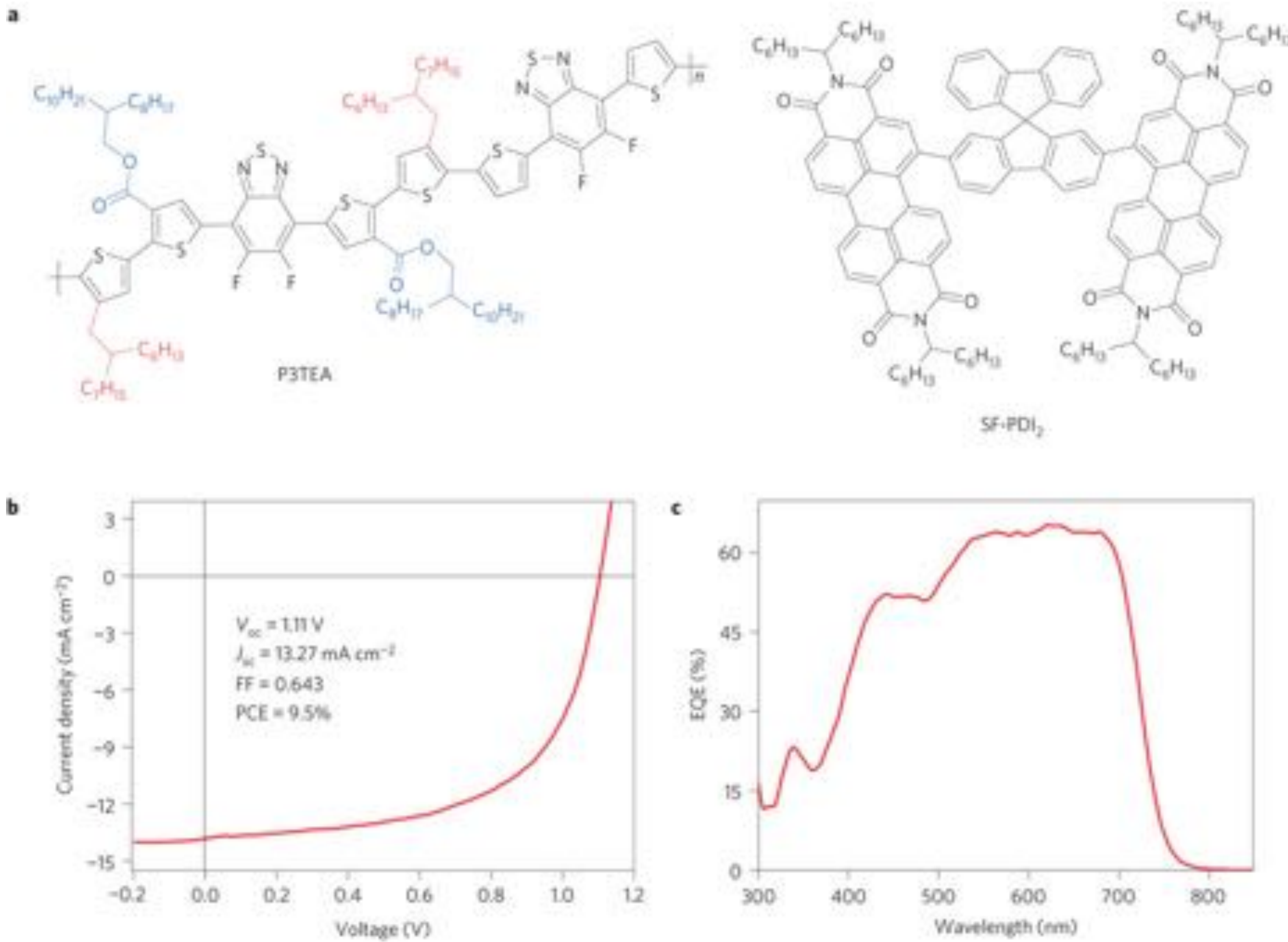
■ 2016, Hong Kong UST, He Yan, best research organic solar cell efficiency 11.7%. [Nature Energy]

fullerene derivative $PC_{71}BM$ as acceptor



■ 2016, Hong Kong UST, He Yan, non-fullerene organic solar cell efficiency 9.5%. [Nature Energy]

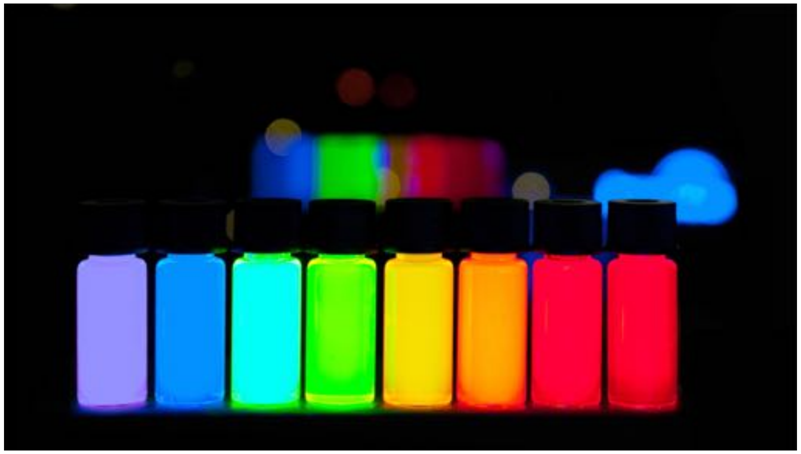
perylene derivative SF-PDI_2 as acceptor



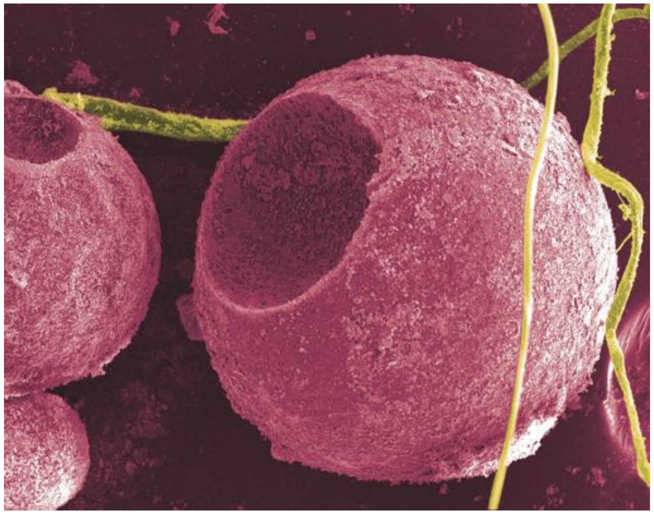
Quantum Dot Solar Cells

■ Quamtum dots: nanometer size semicoductor with bandgaps that are tuable by dots' size.

irradiated with a UV light, larger QDs (5-6 nm) emit orange or red light while smaller QDs emit blue or green light



■ Quamtum dot cells: based on DSSC architecture, employ QDs (CdS, CdSe, PbS etc.) as light absorbers.



Quantum Dot Solar Cells

- 2012, University of Toronto, Edward Sargent, PbS, 7.0% efficiency. [Nature Nanotechnology]
- 2014, University of Toronto, Edward Sargent, air-stable PbS, 8.0% efficiency. [Nature Materials]
- 2014, MIT, Moungi Bawenedi, ZnO/ PbS, 8.5% efficiency. [Nature Materials]
- 2016, University of Toronto, Edward Sargent, 10.6% efficiency. [Nature Energy]
- 2016, University of Toronto, Edward Sargent, 11.3% efficiency. [Nature Materials]