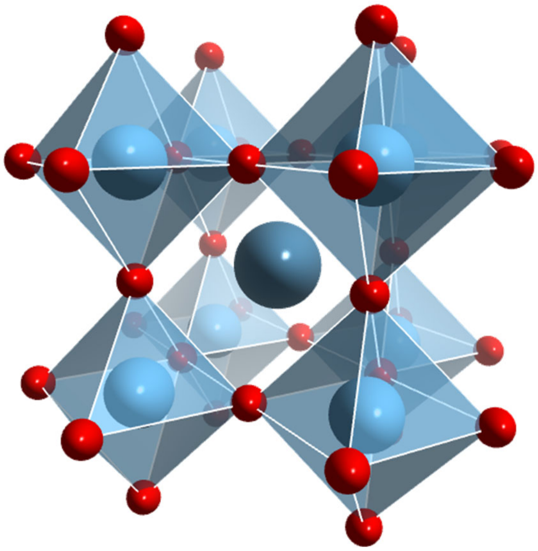
Thursday, 1/29/26

Perovskite Solar Cells

"Perovskite" is a term for materials with an ABX_3 cell structure:

> The term came from $CaTiO_3$, a mineral discovered by Russian mineralogist Lev Perovskite.
>
> The term now applies to any material with this cell structure:



https://www.phy.cuhk.edu.hk/xhlu/index.php/research/perovskite-photovoltaics/

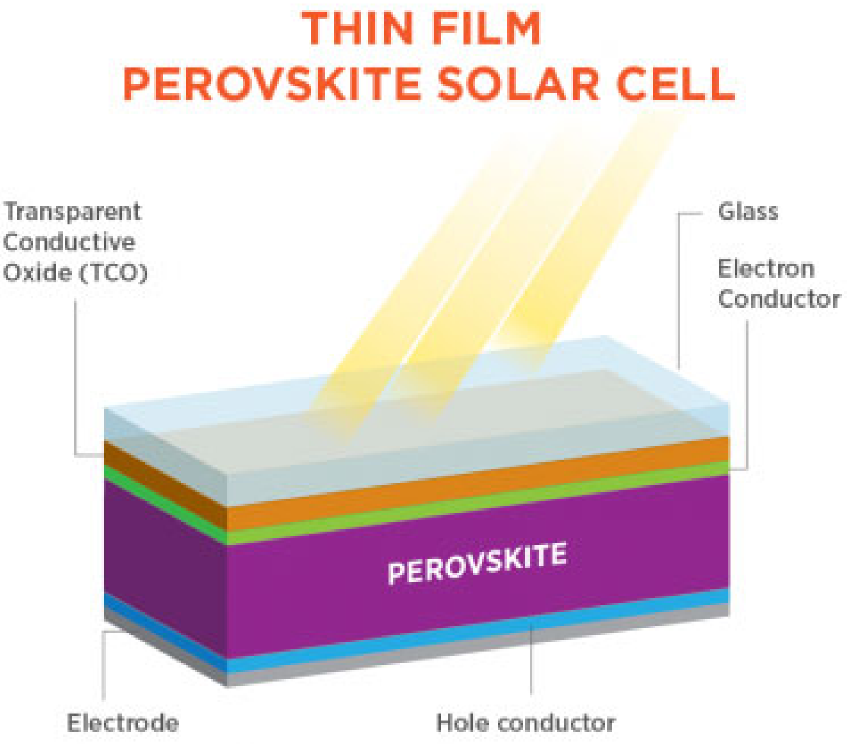
The red spheres are negatively charged ions (anions), such as iodide. The blue spheres surrounded by the red spheres are positively charged ions (cations), such as lead. The center blue sphere is some type of positively charged ion: they are often a combination of organic and inorganic compounds.

When a photon strikes the material, it generates an electron-hole pair.

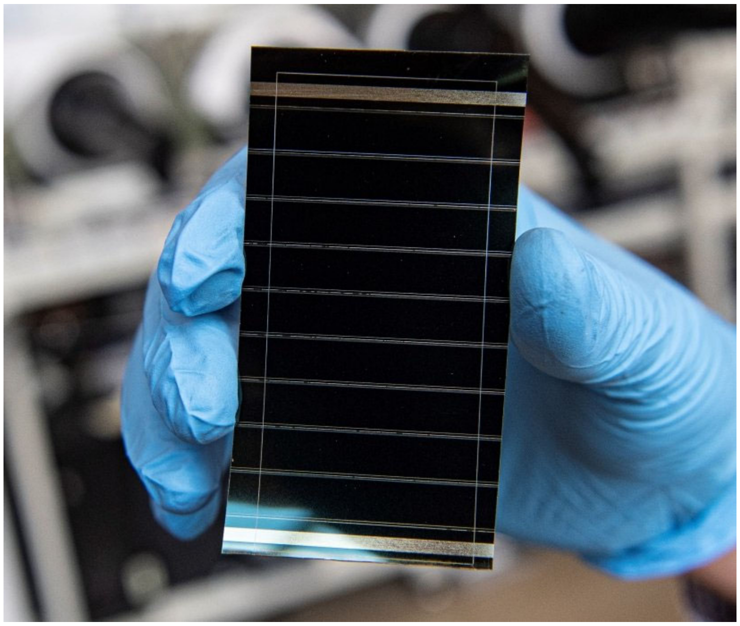
The material can be placed between an electron-sensitive contact and a hole-sensitive contact, realizing a p-i-n (or n-i-p) configuration.

Perovskites are direct bandgap materials and their thin film PV cells have achieved laboratory efficiencies greater than 25%. They can be manufactured using processes such as inkjet printing and thin film deposition by spinning.

There are issues remaining to be solved to realize large scale devices with as high of an efficiency (above about 1 cm^2 in size).



https://www.energy.gov/eere/solar/perovskite-solar-cells



https://www.energy.gov/eere/solar/perovskite-solar-cells

Si Heterojunction PV Technology

This Si PV device has a PIN structure:

P → p-type layer is p-doped a-Si(H), a very thin layer

N → n-type layer is n-doped a-Si(H), a very thin layer

I → intrinsic layer, lightly doped n-type single crystal Si

SC Si: $E_G \sim 1.2$ eV

a-Si(H): $E_G \sim 1.8$ eV

The SC Si has low defect density, high carrier mobility, and minimizes bulk recombination.

The a-Si(H) is thin and therefore easy to dope, has better photon absorption then SC Si, has a higher bandgap that results in a lower loss metallic contact than SC Si (due to less recombination).

a. Structure of the device

Consider the drawings on the next page.

I → n-type <100> SC Si, made by the float zone (FZ) process, and is ~ 300 μm thick.

P → ~ 10 nm thick p-type a-Si(H).

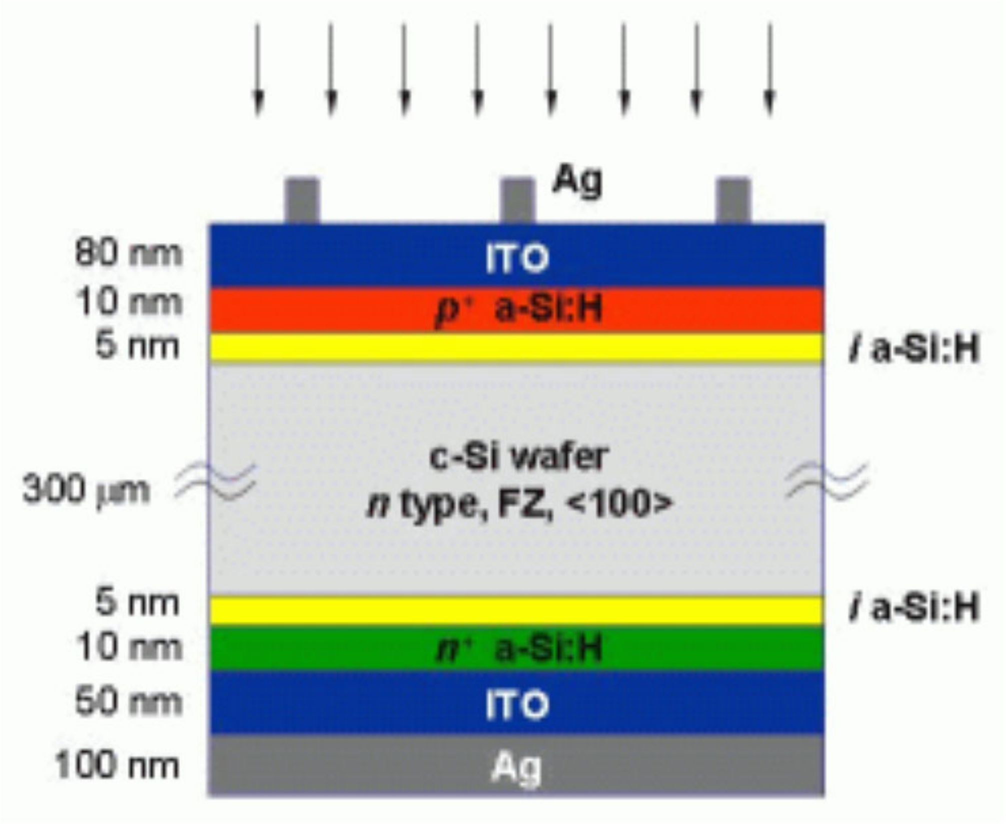
N → ~ 10 nm thick n-type a-Si(H).

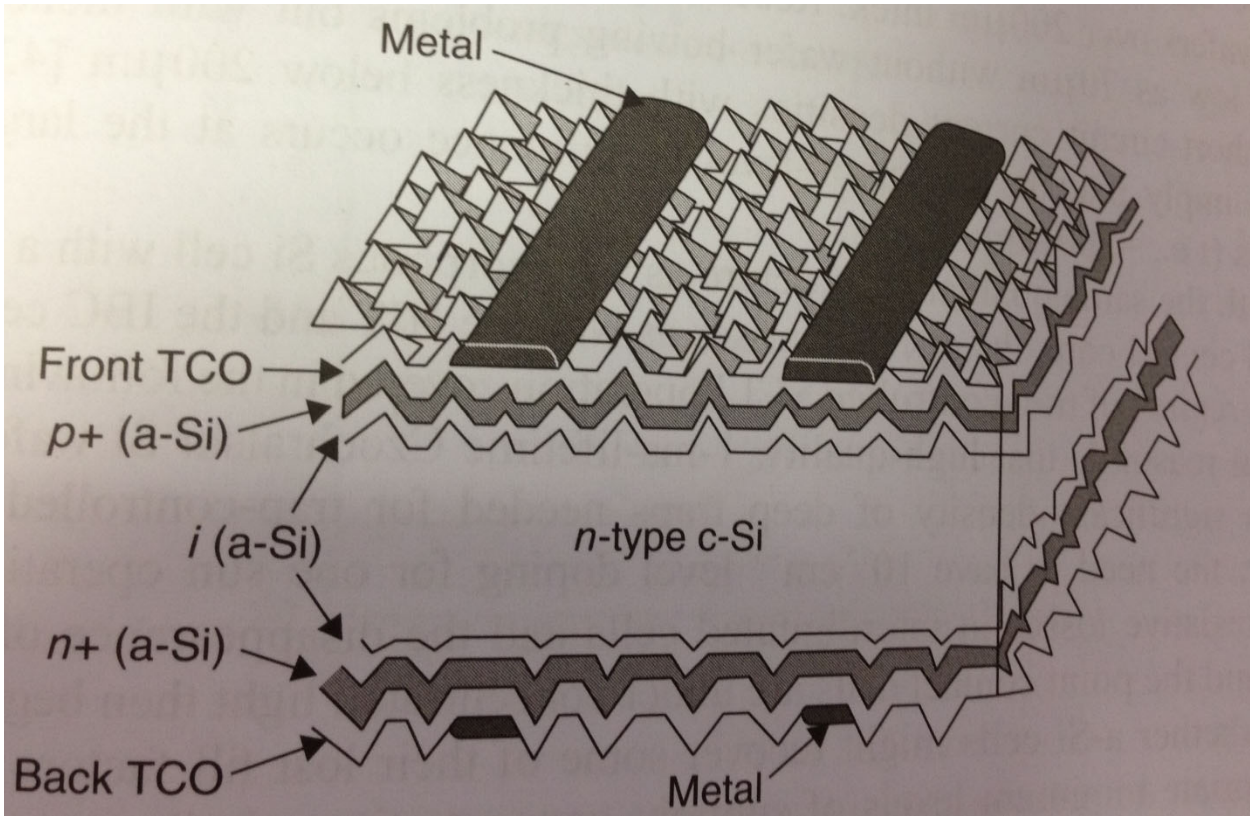
The top ITO (indium tin oxide) layer is a TCO (transparent conductive oxide), which also serves as the ARC, provides a conductive contact to the p-type a-Si(H) layer, and is a passivation layer.

The backside ITO layer provides passivation to the n-type a-Si(H) layer, is a conductive contact layer, and is also a BSF (back surface field) layer.

The Ag layer/features are the metal contacts on the top and bottom.

The textured surfaces reduce reflection losses and increase the photon path length in the cell.


Ag
80 nm
ITO
10 nm
p^+ a-Si:H
5 nm
i a-Si:H
300 μm
c-Si wafer
n type, FZ, <100>
5 nm
i a-Si:H
10 nm
n^+ a-Si:H
50 nm
ITO
100 nm
Ag


Metal
Front TCO
p+ (a-Si)
i (a-Si)
n-type c-Si
n+ (a-Si)
Back TCO
Metal

b. More Information on the Device

This PV device is also called a “HIT cell” and a “Si-HJT”.

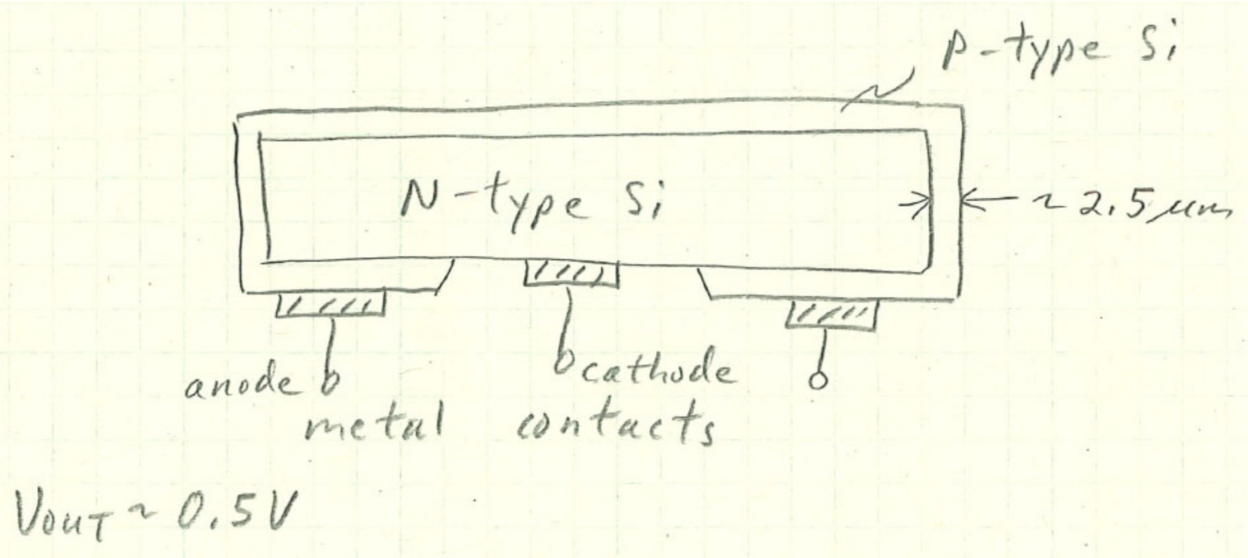
“HIT” → “Heterojunction with Intrinsic Thin-layer”

“Si-HJT” → “HeteroJunction Technology”

Large area devices fabricated (> 100 cm^2) with efficiencies ~ 23% have been reported.

Mass produced devices: 21.8% efficiency with $V_{oc} = 0.718$ V.

Compare the complexity of this 21.8% efficiency HIT cell with a 6% efficiency 1954 Si PV cell:



Die-Sensitized PV Cells (DSCs)

This type of PV cell resembles natural photosynthesis in that:

(1) An organic die is used to absorb light and produce a flow of electrons.

(2) It uses multiple layers to enhance both absorption and collection efficiencies.

Titanium Dioxide (Titania: TiO_2) powder with nanometer sized particles is deposited onto a piece of conductive glass by a process similar to painting.

Titania is a non-toxic white power used in sunscreen and foods. Like other metal oxides, it is a semiconductor material:

(1) It is inexpensive.

(2) It has a large bandgap energy: 3.2 eV, which limits its harvesting of sunlight photons to about 4% of sunlight radiation.

The deposited titania layer forms a nano-porous “sponge”.

The glass plate with the titania “sponge” is dipped in a dye solution, of which there are two primary dyes:

(1) A red ruthenium containing dye. This is an inorganic dye used in paints.
(2) An anthocyanin containing dye. Anthocyanin is a green chlorophyll derivative.

A single layer of dye molecules (a monolayer) attaches to each nano-particle of titania by adsorption.

Consider the drawing below:

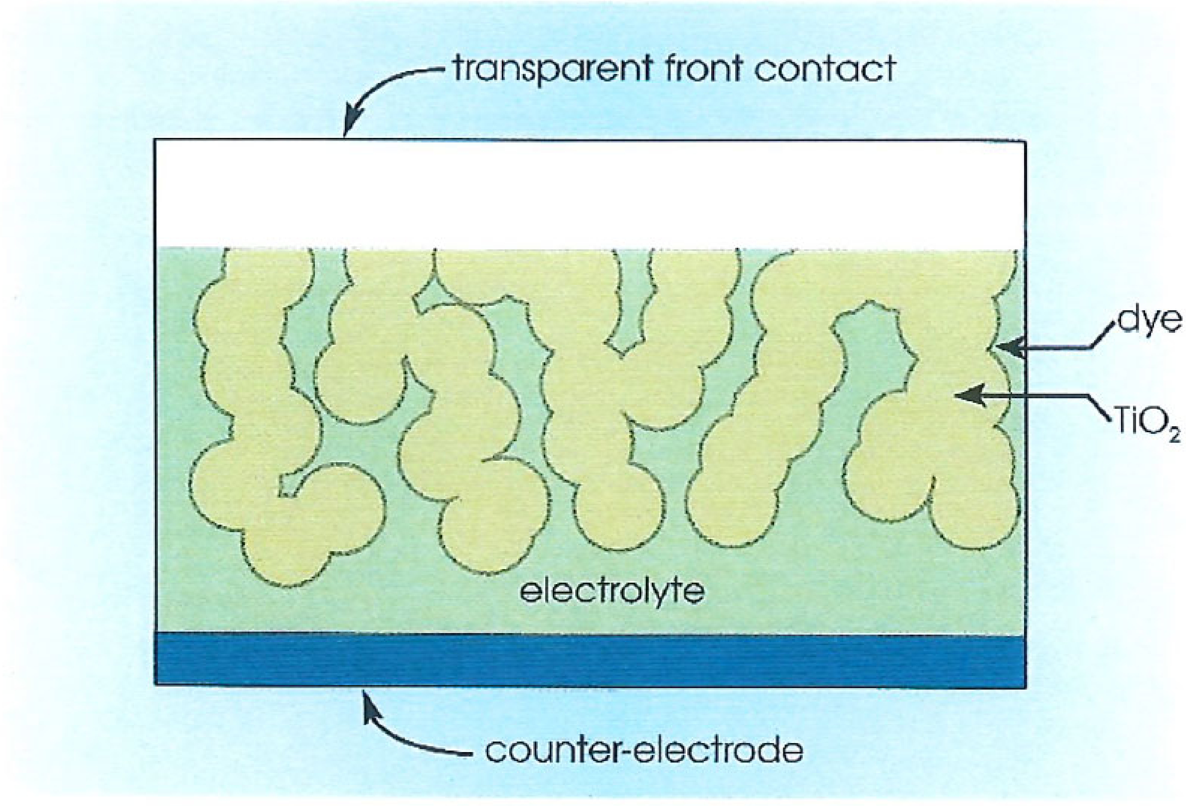


Figure 2.34 A dye-sensitised solar cell.

The dye, also called the TiO_2 “sensitizer”, acts as the primary absorber of sunlight.

An iodide, I^-, containing electrolyte liquid is then placed on the film to percolate into the pores of the membrane.

Then a counter electrode of conductive glass coated with a thin layer of Pt or C, which acts as a catalyst, is placed on top.

The titania side is illuminated by sunlight.

a. So How Does It Work?

Sunlight entering the cell is absorbed by the dye coating the titania nano-particles.

This creates excitation electrons in the dye that are injected into the CB of the titania, causing the dye to oxidize.

The electrons efficiently diffuse through the titania to the electrical contact.

The electrons then pass to and through the attached electrical load.

The electrons then re-enter the cell via the counter electrode.

The electrons then restore the oxidized dye to its original unoxidized state with the help of the electrolyte through a redox chemical process:

$$3I^- \leftrightarrows I_3^- + e^- .$$

Here, recombination does occur, but not with holes, instead it occurs with the oxidized dye.

DSCs are wide bandwidth PV devices, analogous to photosynthesis in plants.

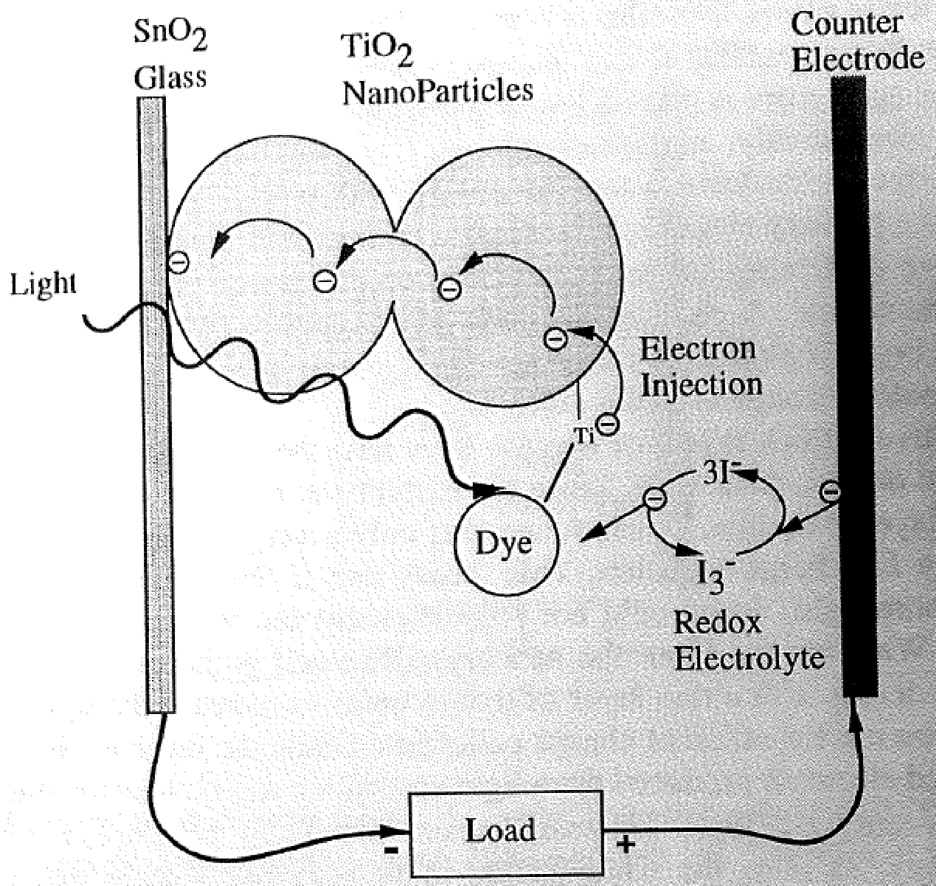


Fig. 4.2 Operation of the dye-sensitized nanocrystalline TiO_2 solar cell. Light is absorbed by the dye molecule (sensitizer) and the resulting excited electron is "injected" into the TiO_2. The electrons then diffuse within the porous TiO_2 structure and are collected at the back contact (conductive transparent glass). The resulting positive charge on the dye is compensated by the mediator, which itself is reduced after the electron has passed through the external load. The redox mediator in the electrolyte goes through cyclic oxidation and reduction as the process continues.

b. The “Graetzel cell” DSC

Also known as the Grätzel cell.

Published in 1991, it was named after its inventor.

It achieved a 10% efficiency at 1000 W/m^2 insolation at 25^{o}C. This efficiency beat a-Si PV cell efficiencies!

The record for a Graetzel cell efficiency is 15% with a ~ 0.7 V V_{oc}.

c. Advantages of DSCs

(1) They are low-cost.

(2) They are made of non-toxic materials.

(3) They can be made to be flexible and realized in many different shapes, and are compatible with various architectural applications:

Figure 2.35 Innovative and flexible: dye-sensitised solar cells in Australia (Dyesol).

(4) They work well in low and diffuse light applications indoors and outdoors.

(5) They work well in high ambient temperatures.

(6) They are simple to make: they can be made in a home kitchen.

Example images of DSC's:

https://en.wikipedia.org/wiki/Dye-sensitized_solar_cell#/media/File:Dye.sensitized.solar.cells.jpg

PV Modules and Arrays, Introduction

How do we get from a single PV cell to a PV module or array, as shown below?

Figure 3.1 A large array of PV modules on a rooftop in Switzerland (EPIA/BP Solar).

What type of PV cell is used above?

Si PV cells are thin and brittle and therefore must be sufficiently protected.

PV cells, in theory, can have a useful lifetime of 20 to 30 years! This length of time becomes challenging for the rest of the system the PV cells are used in.

The PV array containing multiple (many) PV cells must reliably survive in this environment for many years. Consider these issues:

(1) UV light from the sun can damage some materials.

(2) Temperature extremes: summer days to winter nights.

(3) Moisture: can lead to corrosion, cracking from freezing/thawing cycles, electrical shorting, condensation issues.

(4) Snow/ice loading: heavy weight.

(5) Hail damage.

(6) Direct wind damage (thunderstorms, tornado, microburst).

(7) Indirect wind damage: ablation from blowing sand or blowing dirt, damage from larger items being blown into the array.

(8) Impact: falling tree limbs, a kid’s baseball or a rock.

(9) Damage from animals and birds (nesting, poop, chewing on it, digging under it, etc.).

(10) Damage from salt spray and pollution.

(11) How will maintenance and cleaning be performed?

(12) Trees growing up or buildings going up that block the array from direct sunlight for part or all of the time.

(13) Crime and security: someone might intentionally damage the array (riots, vandalism, theft).

(14) Geological issues (foundation settling, earthquakes, ground erosion, sink hole formation).