Glass in energy

Glasses for solar energy III:

PV and photochemical

MAT 498

Lehigh University

The use of glass in solar energy involves two general types of applications:

- bulk glass applications, requiring specific optical, thermal and chemical glass properties, such as glass mirrors and tubing in solar thermal concentrators (in concentrated solar power, CSP);

- applications where glass is essentially a substrate for functional coatings (generally not glassy), which include again CSP (glass mirror substrates), but also low emissivity and solar control glass windows, solar panel glass windows, photovoltaic (PV) panels and photocatalytic (photochemical) self-cleaning glasses.

The scale of solar systems ranges from power plants to individual power units.

The four main applications which will be considered are, therefore:

- solar control glass (namely low emissivity) - lecture 4

- thermal: including solar concentration (parabolic trough and flat heliostat mirror technologies) and solar hot water panels; - lecture 5

→ - photovoltaic (glass containing) panels; - **lecture 6**

- photochemical (namely photocatalytic, self-cleaning glass windows) “

Solar cell inventors at Bell Labs (left to right) Gerald Pearson, Daryl Chapin and Calvin Fuller are checking a Si solar cell sample for the amount of voltage produced (1954).

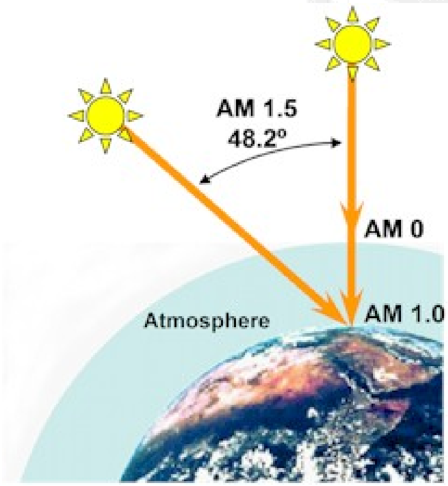
|SOURCE: Courtesy of Bell Labs, Lucent Technologies

Solar Cells

|SOURCE: Courtesy of NASA, Dryden Flight Center

Solar energy is free and basically unlimited. Using it produces no greenhouse gases or other adverse environmental impact. To directly convert this outstanding energy source, however, more efficient photovoltaic (PV) systems must be developed. Whether the development effort involves new semiconductor technology or new concentrator designs, solar simulation systems will be play integral part.

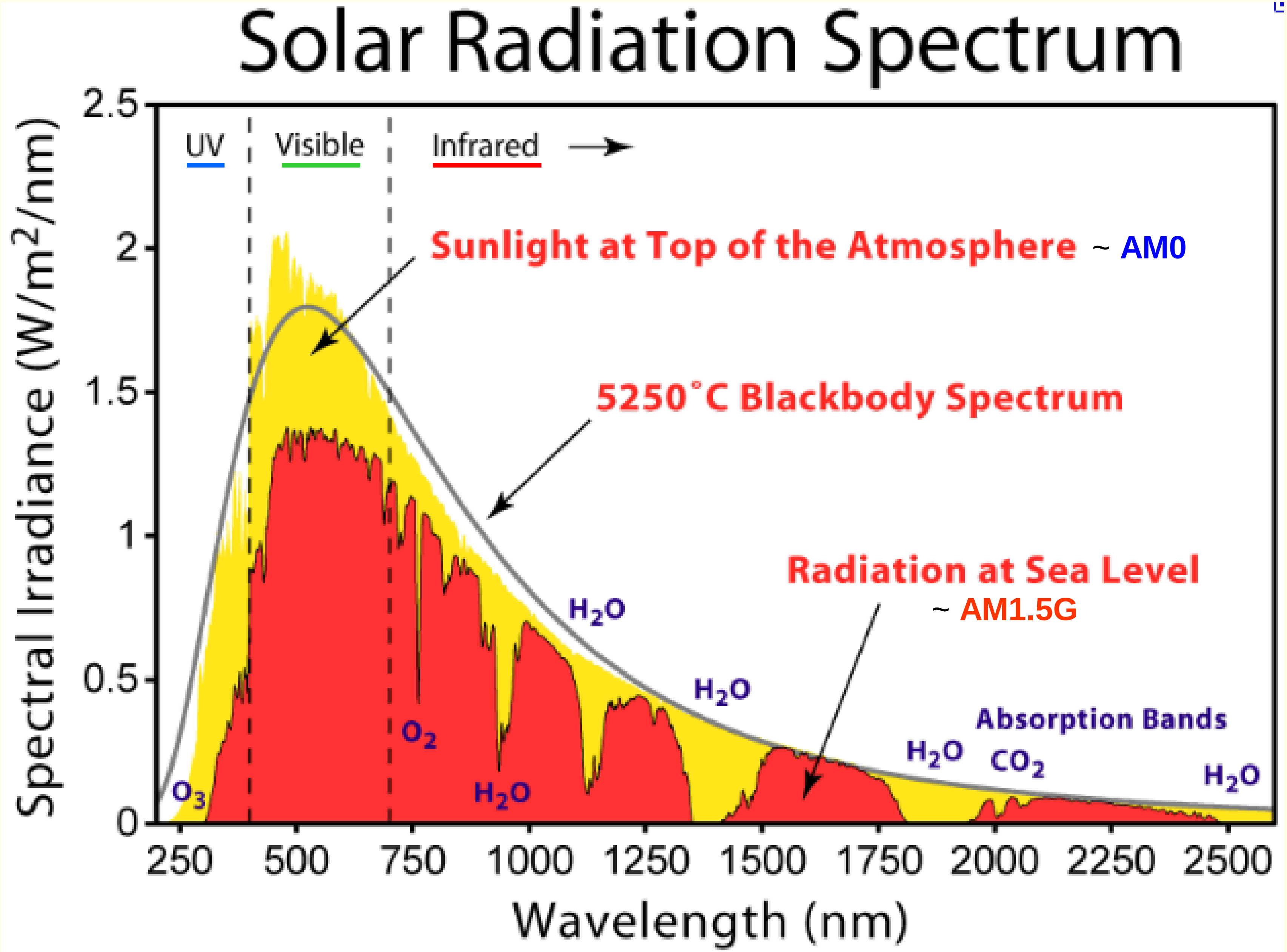
Solar simulation is much more than just choosing a lighting source with a spectrum that "looks good". The whole premise behind artificial solar simulation is to replicate, as accurately as possible, the effects of actual sunlight on products or PV material. Whether you are trying to measure the detrimental effects of UV or the beneficial output of PV panels, this data must parallel the results from actual sunlight and be repeatable. For this reason, international standards have been developed to benchmark solar simulation lighting. The current ASTM G173-03 and IEC 60904-3 international standards (see below) quantify the solar radiation energy level across the spectrum from 280nm to 4000nm.



Air Mass is the measure of how far light travels through the Earth's atmosphere. One air mass, or AM1, is the thickness of the Earth's atmosphere. Air mass zero (AM0) describes solar irradiance in space, where it is unaffected by the atmosphere. The power density of AM1.5 light is about 1,000W/m^2; the power density of AM0 light is about 1,360W/m^2, which is considered to be the solar constant.

For PV testing (terrestrial use), the Standard Test Condition (STC) is defined as an insolation of 1000W/m^2 (1 SUN) at 25 °C and with a solar spectral distribution equivalent to global AM1.5, per ASTM G173-03 and IEC 60904-3. For solar simulation performance classification, a spectral irradiance distribution standard has been established.

Adapted from: http://www.google.co.uk/imgres?q=solar+radiation+spectrum&hl=pt- (20 Jan 2012)

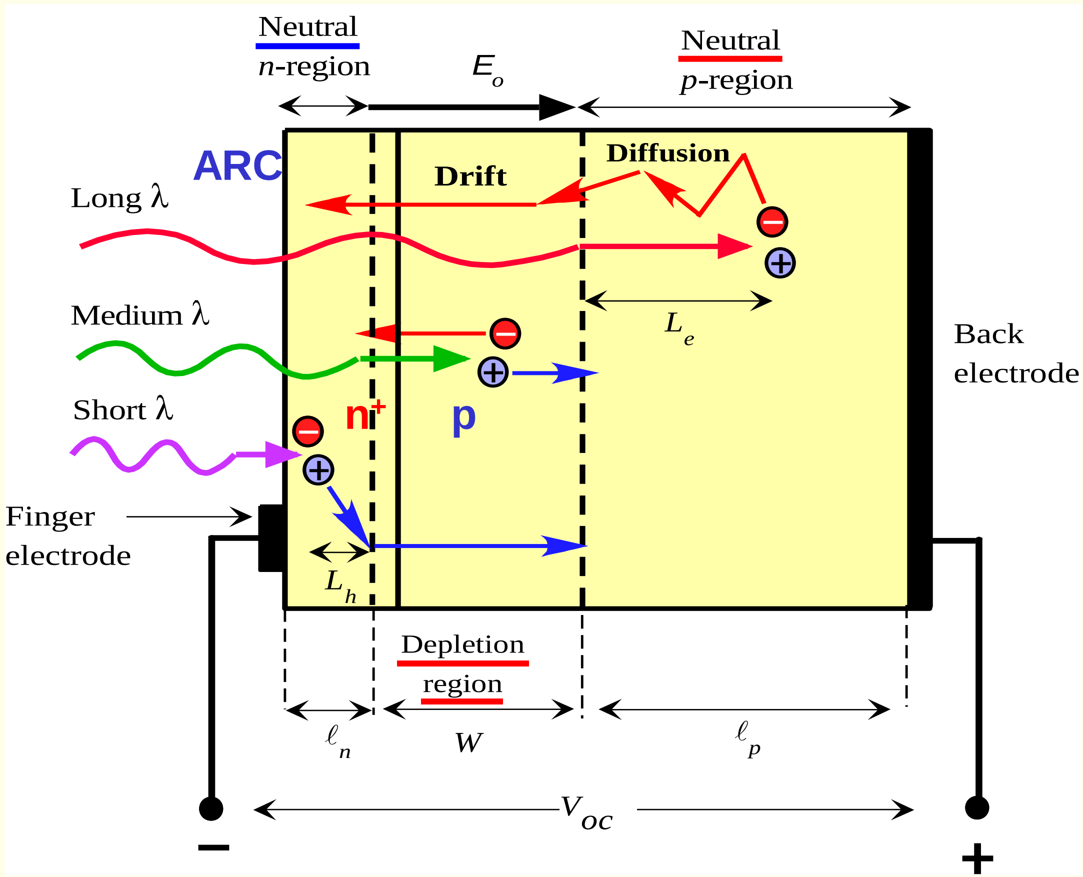


Adapted from: http://www.google.co.uk/imgres?q=solar+radiation+spectrum&hl=pt- (20 Jan 2012)

Photovoltaic

solar cells

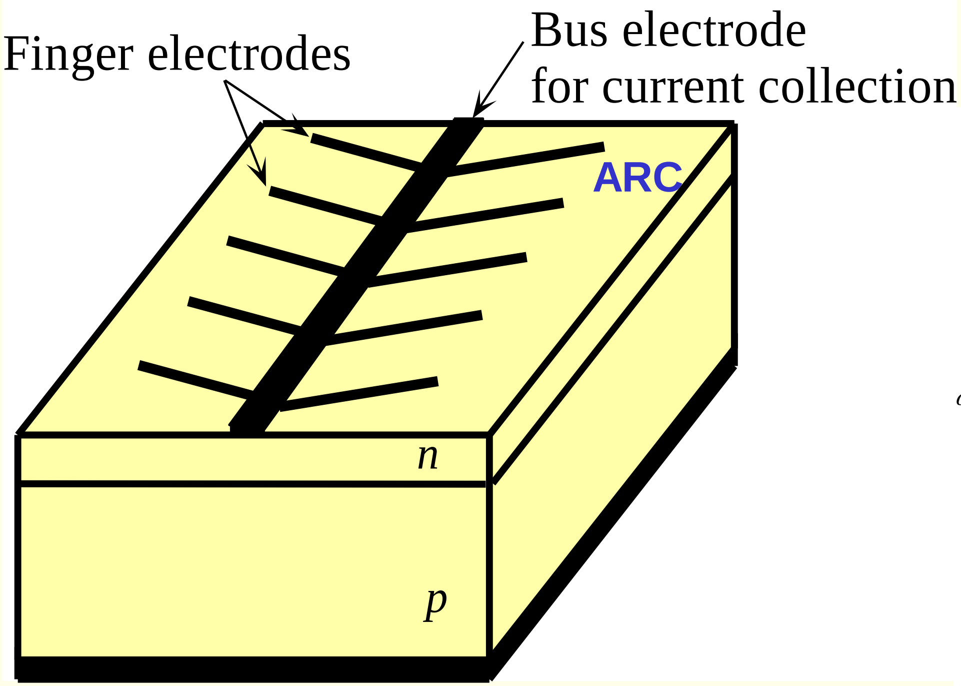
In a **photovoltaic** **(PV)** **p-n junction solar cell**, above bandgap sunlight *photogenerates* electron-hole pairs (EHPs) in the depletion region (DR) which are immediately separated by E_o and an *open-circuit voltage*, V_{oc} , develops.

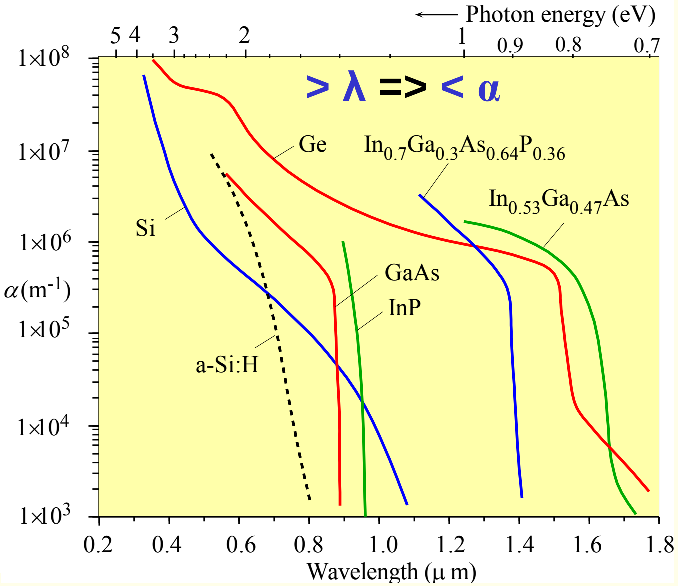


The principle of operation of the solar cell (exaggerated features to highlight principles)

From: *Principles of Electronic Materials and Devices*, *Third Edition*, S.O. Kasap (© McGraw-Hill, 2005)

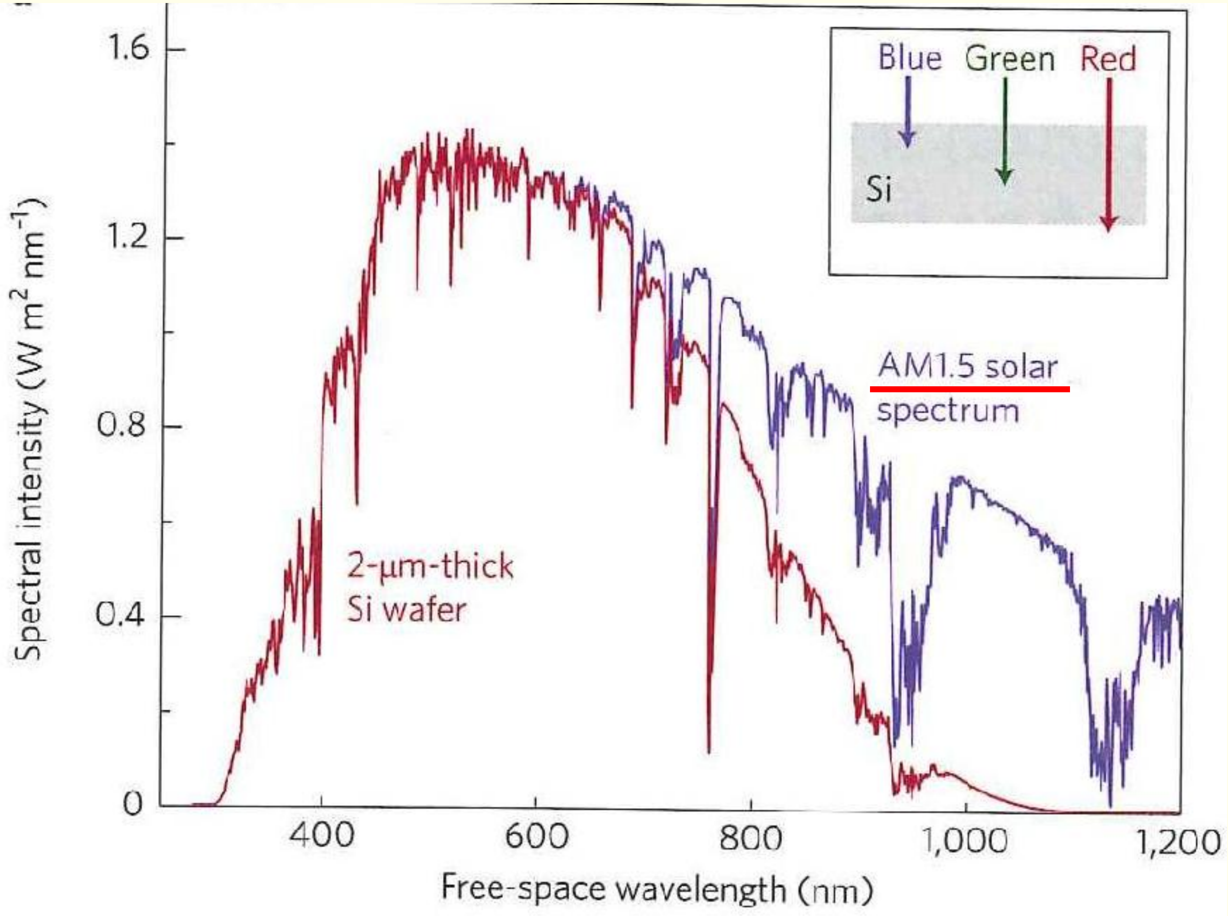
For Si, incident energy with λ > 1.1 μm (~ 25%) is wasted. The worst part of the efficiency limitation, however, comes from the high energy (visible) photons being absorbed near the crystal surface and lost by EHP *recombination* in the *surface centers*, causing losses as high as 40%. These effects bring the efficiency down to ~ 45%. Including the limited action of the AR coating and other factors, the **single crystal Si photovoltaic efficiency is ≤ 25%**.





Finger electrodes on the surface of a solar cell reduce the series resistance

From: *Principles of Electronic Materials and Devices*, *Third Edition*, S.O. Kasap (© McGraw-Hill, 2005)



Optical absorption and carrier diffusion requirements in a solar cell. a, AM1.5 solar spectrum, together with a graph that indicates the solar energy absorbed in a 2-μm-thick crystalline Si film (assuming single-pass absorption and no reflection). Clearly, a large fraction of the incident light in the spectral range 600–1,100 nm is not absorbed in a thin crystalline Si solar cell. **b**, Schematic indicating carrier diffusion from the region where

This leads to the need for up-conversion (and also down-conversion) techniques for Si solar cells.

For a Si solar cell, e.g., n (Si) ~ 3.5 @ 700-800 nm and the ***external*** reflectance (from air, with an index $n_1 = 1$) is $R = [(n-1)/(n+1)]^2 = 0.309$, so ~ 30% of the incident light is reflected, with a considerable reduction in efficiency. By coating the surface of the SC with a thin dielectric layer of Si_3N_4 ($n_2 \sim 1.9$), which has an index $n_2 \sim (n_1 n_3)^{1/2}$, with a thickness ***d*** such that light waves A and B interfere destructively, i.e. ***d*** = m $\lambda/4n_2$ (m = 1, 3, 5, ...), the reflected light is significantly reduced.

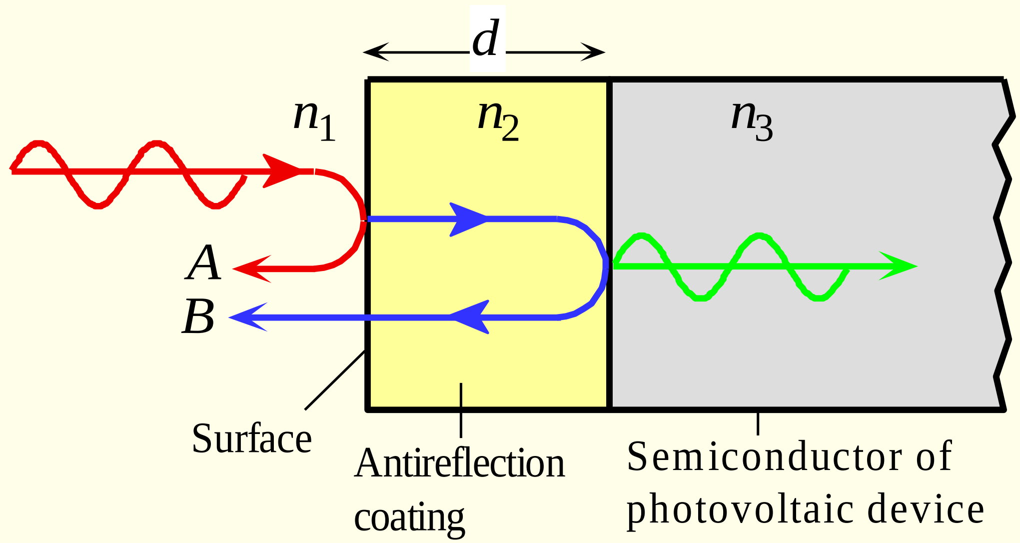
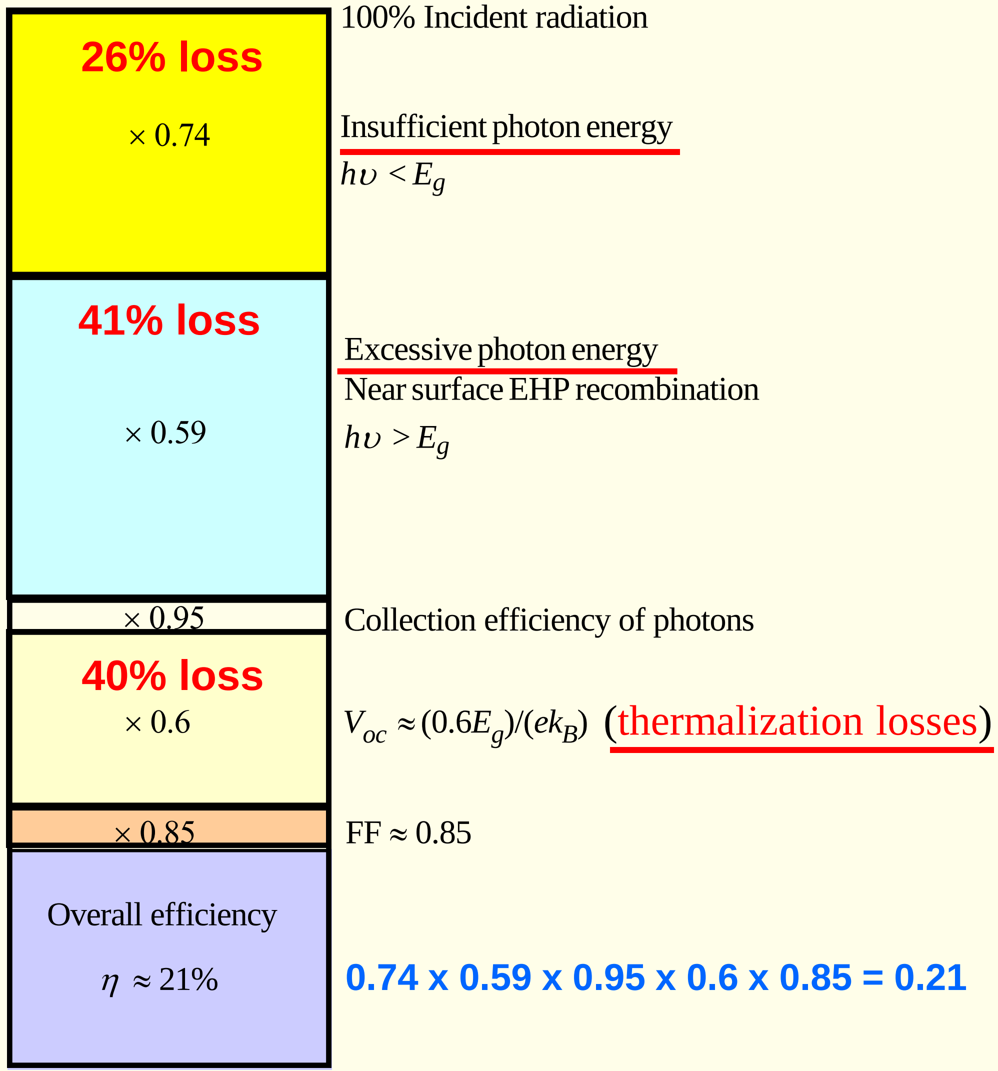


Illustration of how an antireflection coating reduces the reflected light intensity

From: *Principles of Electronic Materials and Devices*, *Third Edition*, S.O. Kasap (© McGraw-Hill, 2005)

The **fill factor**, FF, is a *figure of merit* for the solar cell and it should be as close to 1 as possible.



Accounting for various losses of energy in a high efficiency Si solar cell. Adapted from C. Hu and R. M. White, *Solar Cells* (McGraw-Hill Inc, New York, 1983, Figure 3.17, p. 61).

Table 6.3 Typical characteristics of various solar cells at room temperature under AM1.5 illumination of 1000 W m^{-2}

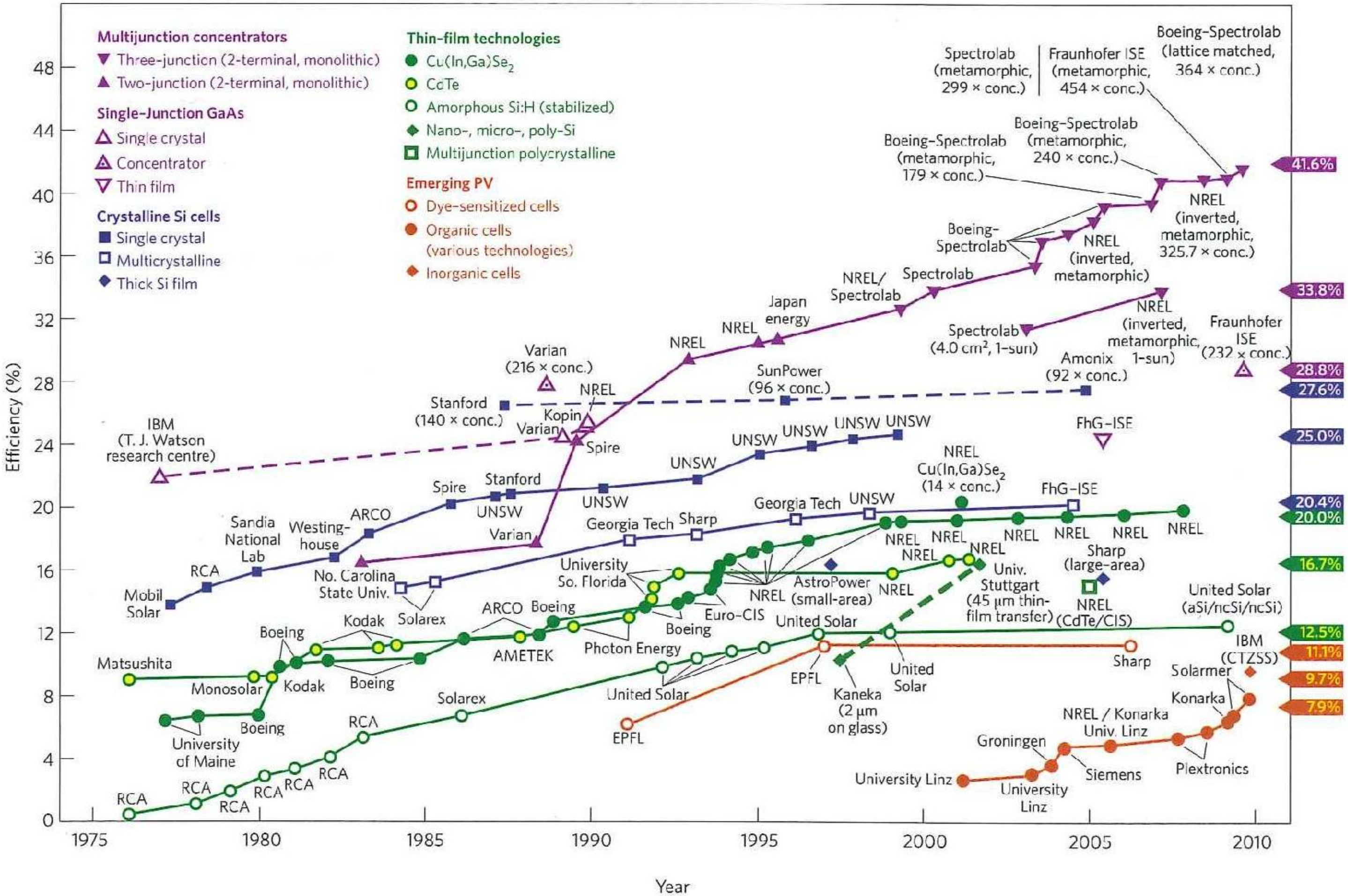
Semiconductor	E_g (eV)	V_{oc} (V)	J_{sc} (mA cm^{-2})	FF	η (%)	Comments
Si, single crystal	1.1	0.5–0.7	42	0.7–0.8	16–24	Single crystal, PERL
Si, polycrystalline	1.1	0.5–0.65	38	0.7–0.8	12–19	
Amorphous Si:Ge:H film					8–13	Amorphous film with tandem structure, convenient large-area fabrication
GaAs, single crystal	1.42	1.02	28	0.85	24–25	
GaAlAs/GaAs, tandem		1.03	27.9	0.864	24.8	Different bandgap materials in tandem increases absorption efficiency
GaInP/GaAs, tandem		2.5	14	0.86	25–30	Different bandgap materials in tandem increases absorption efficiency
CdTe, thin film	1.5	0.84	26	0.75	15–16	
InP, single crystal	1.34	0.87	29	0.85	21–22	
$CuInSe_2$	1.0				12–13	

NOTE: AM1.5 refers to a solar illumination of "Air Mass 1.5," which represents solar radiation falling on the Earth's surface with a total intensity (or irradiance) of 1000 W m^{-2}. AM1.5 is widely used for comparing solar cells.

(Heterojunctions and tandem cells minimize the efficiency losses of Si solar cells due to low energy unabsorbed photons (hν < 1.1 eV) and short-λ photons absorbed only near the surface (which total ~ 40% losses**)).**

Q.

From: *Principles of Electronic Materials and Devices*, *Third Edition*, S.O. Kasap (© McGraw-Hill, 2005)



Efficiencies refer here to small lab cells; commercial modules have efficiencies ~ 20 – 50% lower.

Evolution of the best laboratory cell efficiencies for different solar cell technologies. The plot distinguishes three generations of solar cells according to their state of development. First-generation cells are made of single-layer p–n junction diodes of GaAs or silicon wafers. The second-generation cells are thin films of materials such as amorphous silicon, CdTe and $CuInSe_2$ (CIGS). Third-generation cells are emerging PV technologies such as dye-sensitized cells and various organic cell technologies. Multijunction concentrator cells are a separate PV category that currently achieves efficiencies over 40%. (Figure courtesy of L. Kamarski, NERL USA, April 2010.)

Adapted from: J-M Tarascon & Michael Gratzel, Materials for Sustainable Energy, ed. Vincent Dusastre (NPG, London, 2011), p. XIII.

Table 1 Performance of photovoltaic and photoelectrochemical solar cells

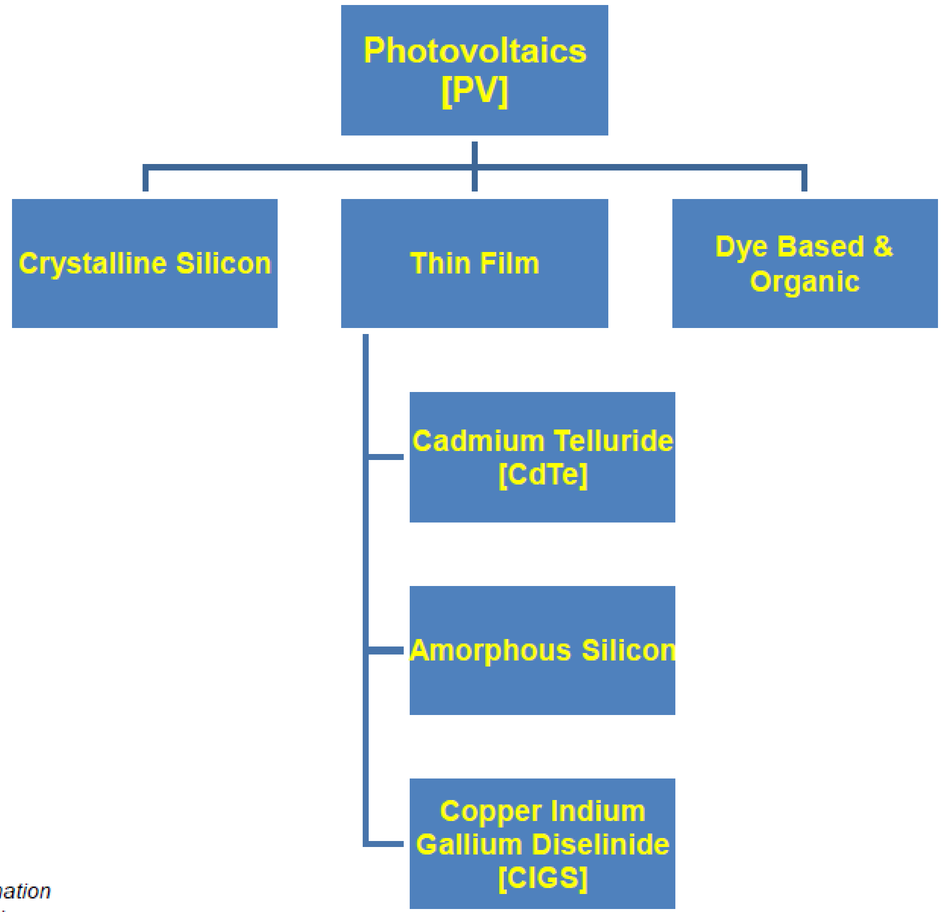
	Type of cell	Efficiency (%)* Cell	Efficiency (%)* Module	Research and technology needs
1st gener.	Crystalline silicon	24	10–15	Higher production yields, lowering of cost and energy content
1st gener.	Multicrystalline silicon	18	9–12	Lower manufacturing cost and complexity
2nd gener.	Amorphous silicon	13	7	Lower production costs, increase production volume and stability
2nd gener.	$CuInSe_2$ CdTe	19	12	Replace indium (too expensive and limited supply), replace CdS window layer, scale up production
3rd gener.	Dye-sensitized nanostructured materials	10–11	7	Improve efficiency and high-temperature stability, scale up production
3rd gener.	Bipolar AlGaAs/Si photoelectrochemical cells	19–20	—	Reduce materials cost, scale up
3rd gener.	Organic solar cells	2–3	—	Improve stability and efficiency

*Efficiency defined as conversion efficiency from solar to electrical power.

Adapted from: Michael Gratzel, Nature 414 (2001) 338 – 344.

Photovoltaics

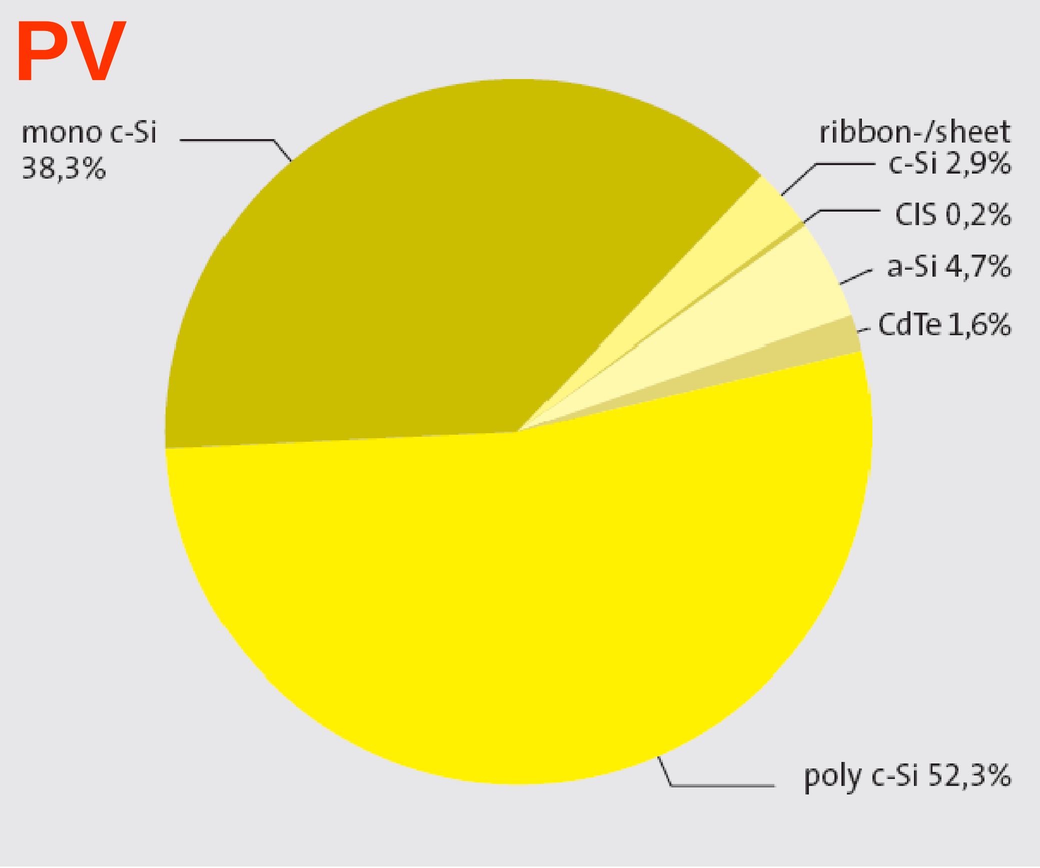
Solar Industry Market Structure



DOE
Energy Information Administration

Adapted from: The future of High Performance Glazing in Commercial Buildings, James J. Finley (PPG Industries, Inc.), International Workshop on Glass for Harvesting, Storage and Efficient Usage of Solar Energy, Nov. 16-18, 2008, Pittsburgh, PA

Market Evolution



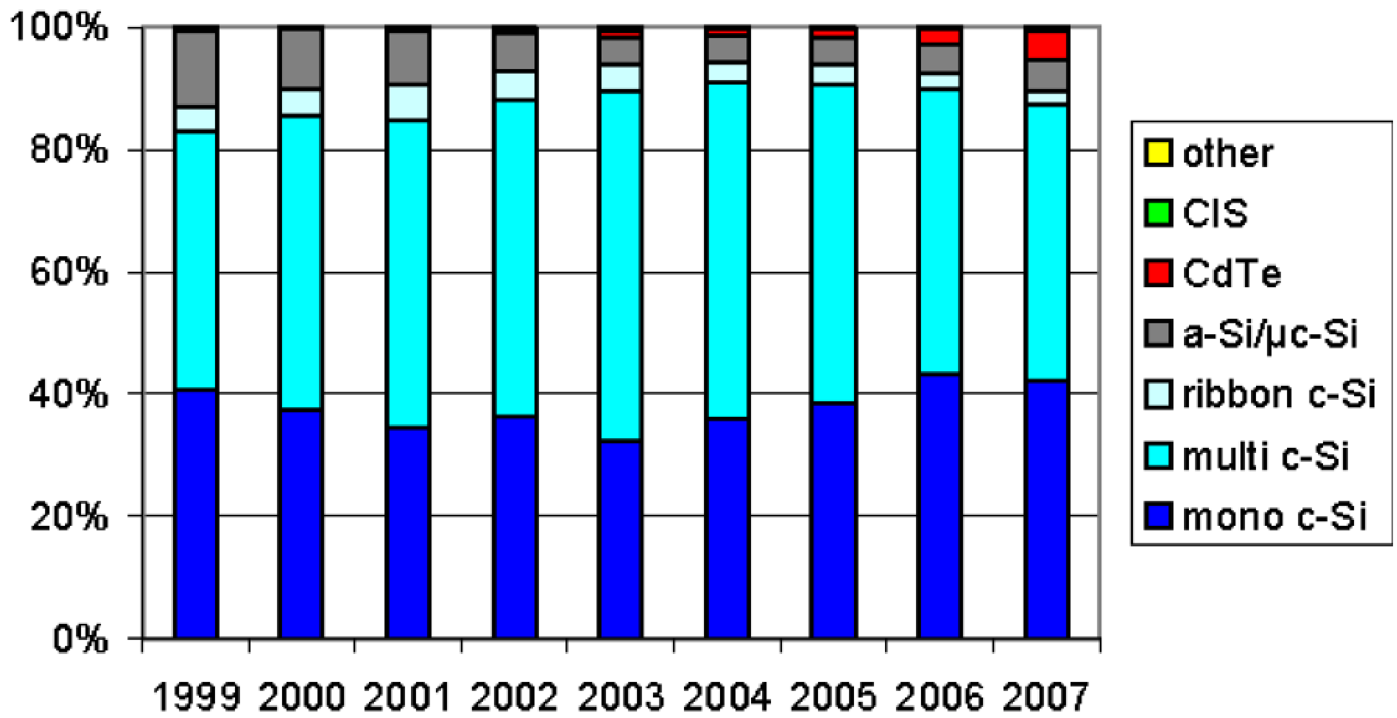
Source: "Photon International", March 2006

Table 1.1: Module and cell efficiencies

Type	Typical module efficiency (%)
Single crystalline cell [mono c-Si]	12–15
Multicrystalline silicon [Multi c-	11–14
Amorphous silicon [a-Si]	5–7
Cadmium telluride [CdTe]	6–7.5
CIS	9–9.5
a-Si/m-Si	10

Source: International Energy Agency (IEA) Photovoltaic Power Systems Programme,

PV Technologies



Source: PHOTON International March 2008

MOMENTIVE
performance materials

Adapted from: Fused quartz in the PV market, Martin Panchula (Momentive Performance Materials), International Workshop on Glass for Harvesting, Storage and Efficient Usage of Solar Energy, Nov. 16-18, 2008, Pittsburgh, PA

Silicon PV solar cells

Monocrystalline silicon is the most efficient and produces the smallest solar cells, and therefore the smallest panels. Monocrystalline solar panels are also the most expensive ($).

Polycrystalline (or multi-crystalline) silicon produces the next most efficient type of solar cell and is the most popular choice as it provides an excellent balance of performance and economy. Recent improvements in polycrystalline panel technology are bringing these modules closer to monocrystalline, in size, efficiency and heat tolerance characteristics. The european market has now adopted polycrystalline as the standard.

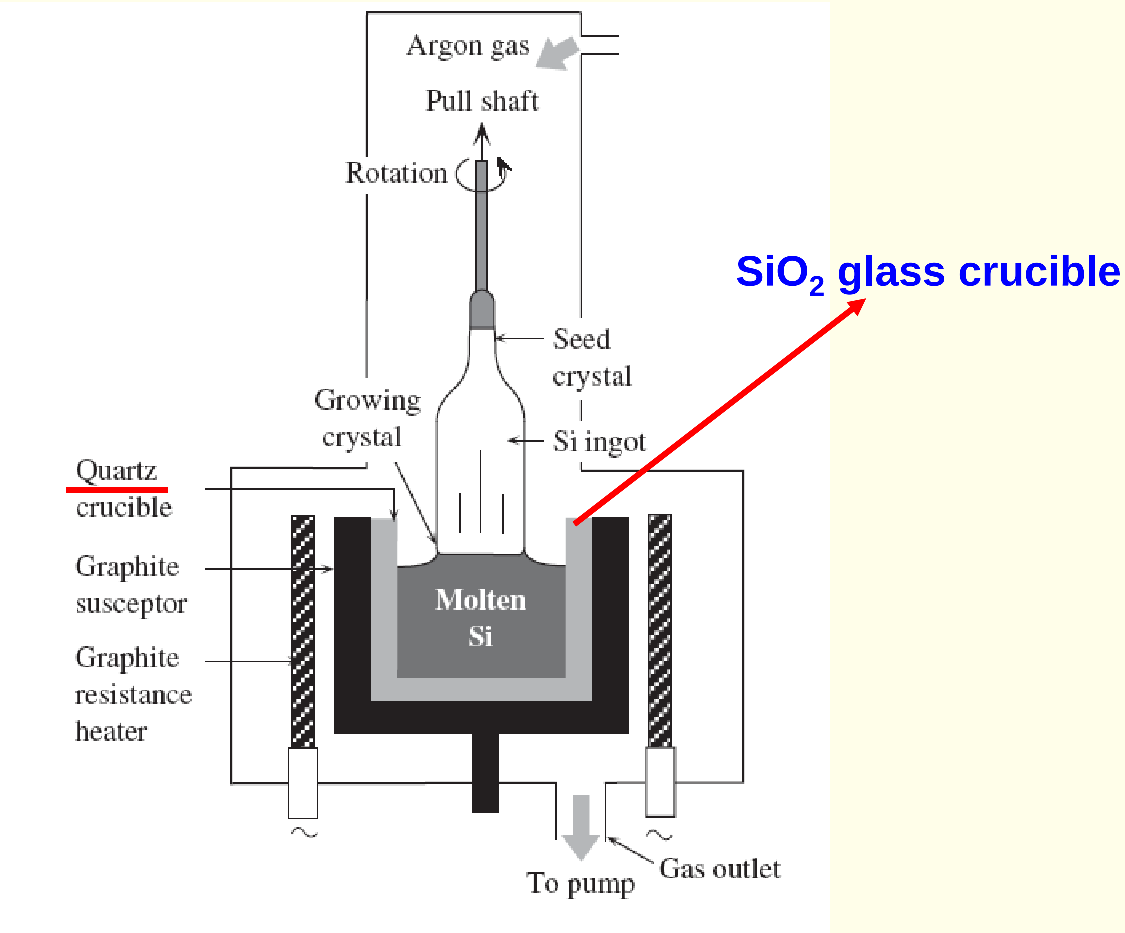
Amorphous (or thin-film) silicon uses the least amount of silicon and also produces the least efficient solar cells. This means thin film system take up more area than the other two; an important factor to consider in relation to possible future upgrades, when there is enough space.

In most situations, the use of quality polycrystalline solar panels for home solar power systems is probably the best choice.

Q.

Where is glass used in PV?

Ultrapure polycrystalline Si (obtained by the reduction of silica to impure silicon, followed by chlorination to liquid $SiCl_4$, its ultrapurification by distillation and reduction in H_2 atmosphere) is melted in a **silica glass crucible** under inert atmosphere and a seed Si crystal with a bottom face with a (100) or (111) orientation is clamped to a metal rod and dipped into the melt.

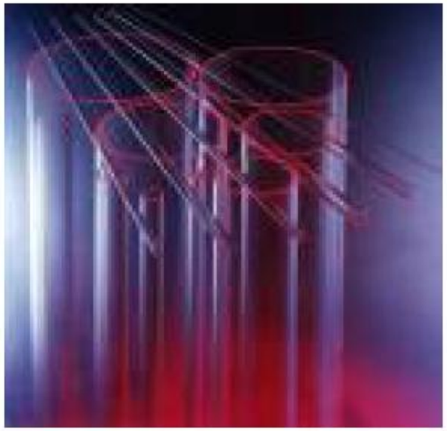


(a) Schematic illustration of the growth of a single-crystal Si ingot by the Czochralski technique.

From: *Principles of Electronic Materials and Devices*, *Third Edition*, S.O. Kasap (© McGraw-Hill, 2005)

Why Fused Quartz?

- Unique material
  - Purity – typically >99.995%
  - High Temperature
    - Softening – 1683 C
    - Annealing – 1220 C
    - Strain – 1120 C
  - Low CTE – 0.55 ppm/C **(α_T x 10^{-6} $^oC^{-1}$)**
  - Chemically stable
    - Stable against most acids and bases
    - Slow dissolution into Si melt
  - Versatile
    - Accepts dopants, secondary phases
    - Ground, polished, welded
    - Stable glass



MOMENTIVE
performance materials

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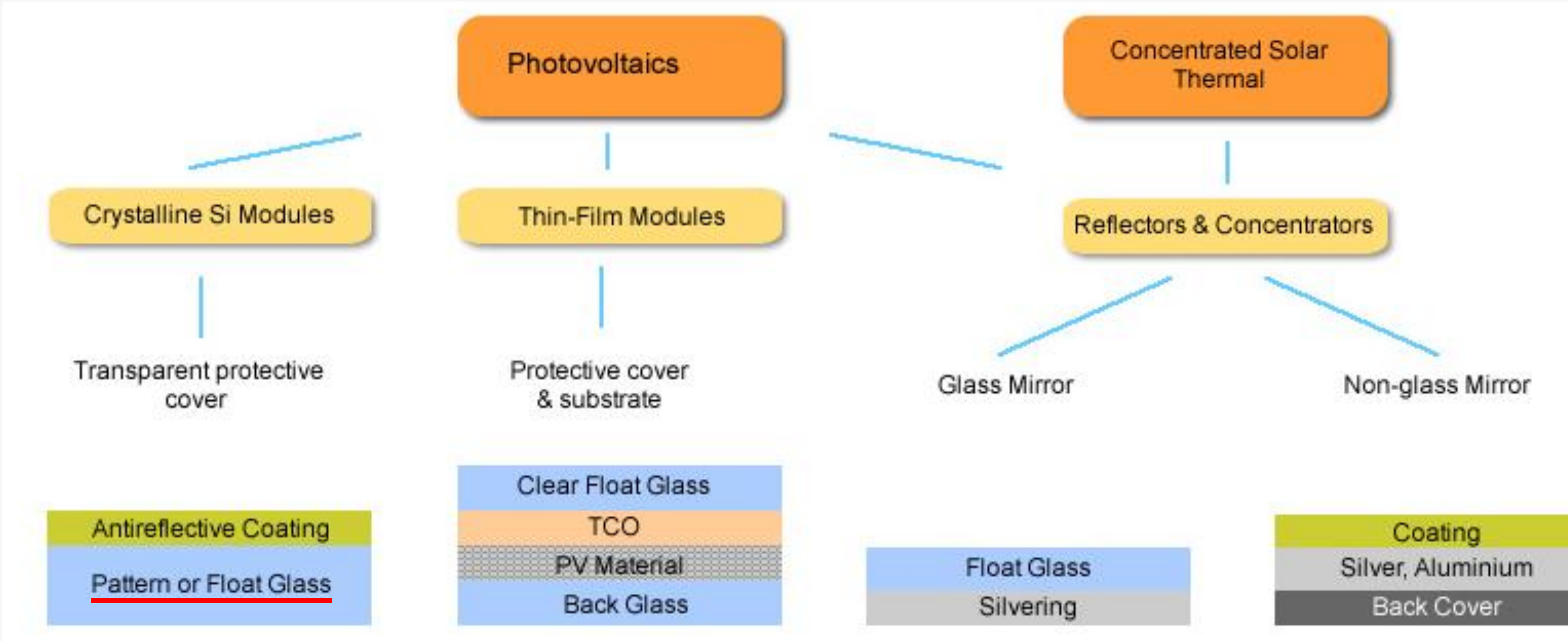
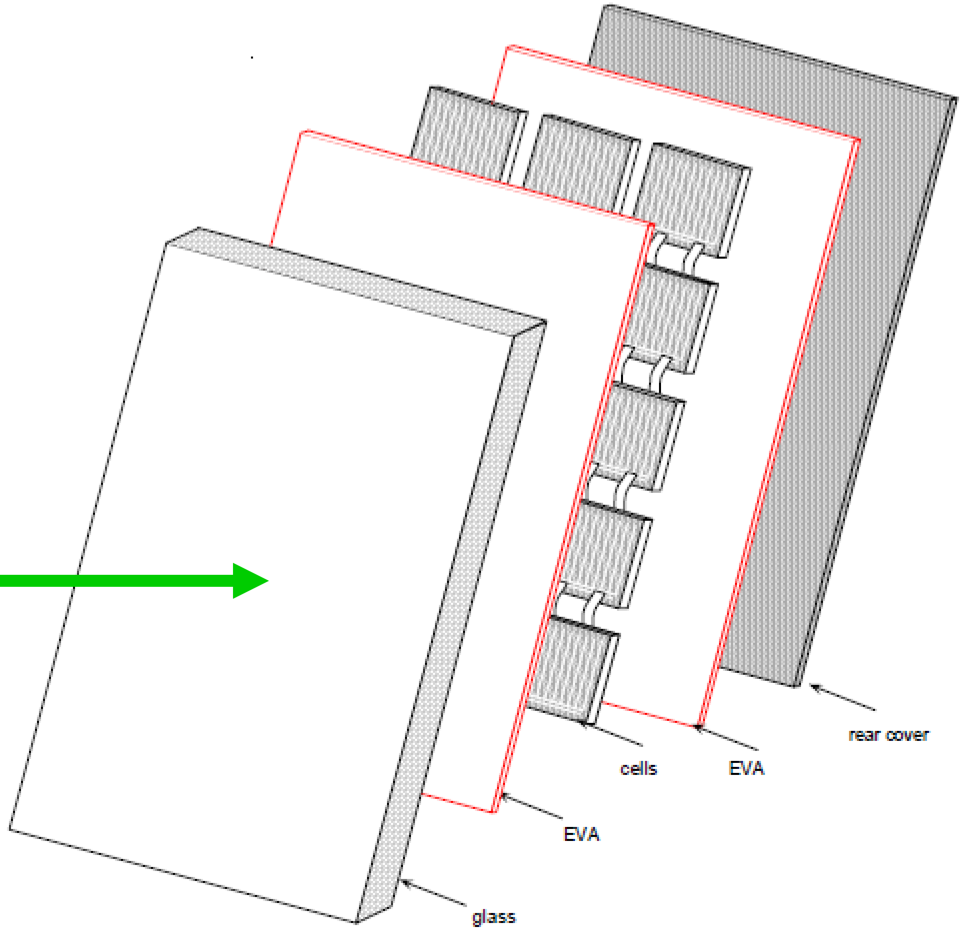
Adapted from: Fused quartz in the PV market, Martin Panchula (Momentive Performance Materials), International Workshop on Glass for Harvesting, Storage and Efficient Usage of Solar Energy, Nov. 16-18, 2008, Pittsburgh, PA

Solar Glass & Mirrors → Silicate glass

Glass is used in photovoltaic modules as layer of protection against the elements. In thin-film technology, glass also serves as the substrate upon which the photovoltaic material and other chemicals (such as TCO) are deposited. Glass is also the basis for mirrors to concentrate sunlight, although new technologies avoiding glass are emerging.



Adapted from: Solar Glass & Mirrors, Gree Rhino Energy Ltd. Website (7 Dec. 2011) sunlight

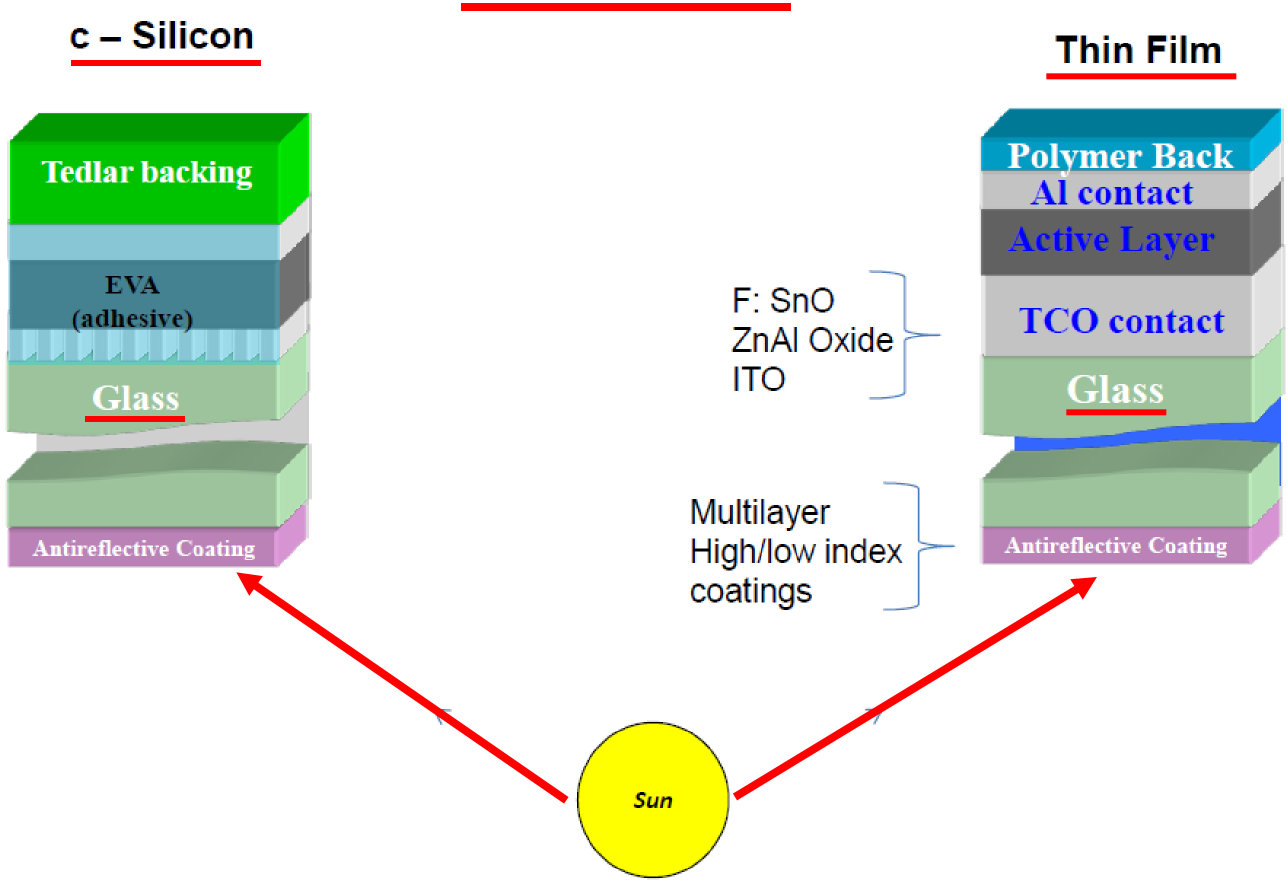


Exploded view of a standard silicon photovoltaic module. The different layers shown are laminated together under pressure at a temperature around 140–150 C where the transparent EVA (ethylene vinyl acetate) softens and binds the different layers together on cooling. Source: Green and Hansen (1998).

Adapted from: http://www.icpress.co.uk/etextbook/p139/p139_chap4.pdf (#0 Jan 2012)

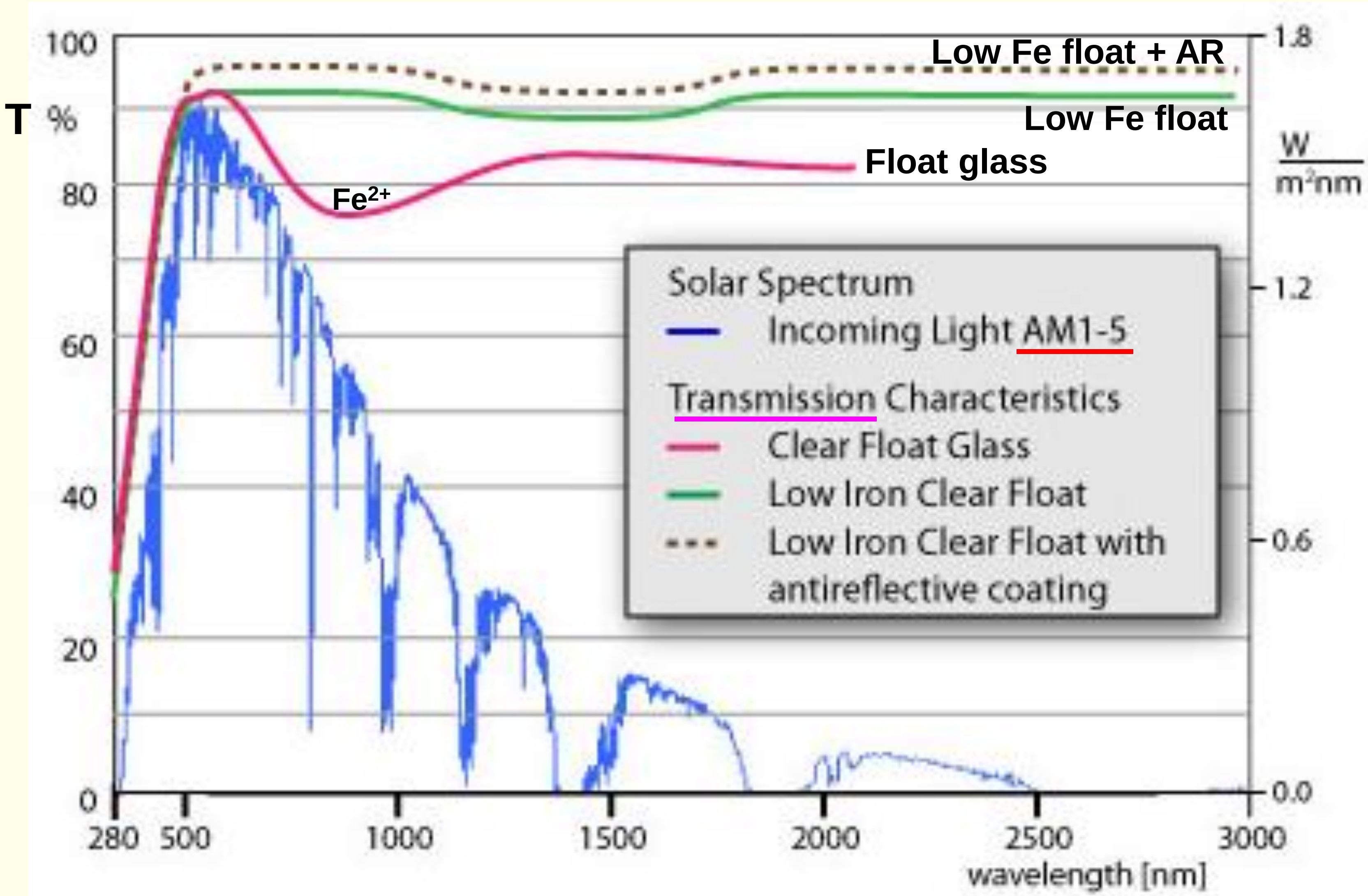
Photovoltaics

Modules



Adapted from: The future of High Performance Glazing in Commercial Buildings, James J. Finley (PPG Industries, Inc.), International Workshop on Glass for Harvesting, Storage and Efficient Usage of Solar Energy, Nov. 16-18, 2008, Pittsburgh, PA

Need for low Fe glass



Adapted from: Solar Glass & Mirrors, Gree Rhino Energy Ltd. Website (7 Dec. 2011)

Glass Production Infrastructure

GUARDIAN
Glass · Automotive · Building Products

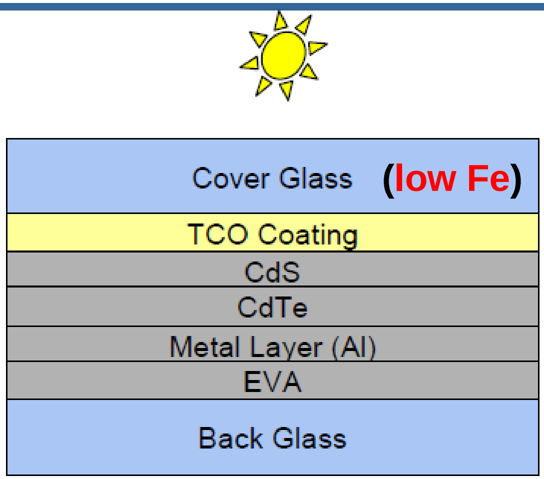
- Low iron containing materials are essential for solar glass production (T_{solar} ~ 90%, on a 3 mm float plate)

- Single largest challenge for low iron solar pattern and float production is sourcing of the raw materials
  - Low iron sand
  - Low iron dolomite (may be removed)
  - Low iron limestone
  - Low iron glass cullet

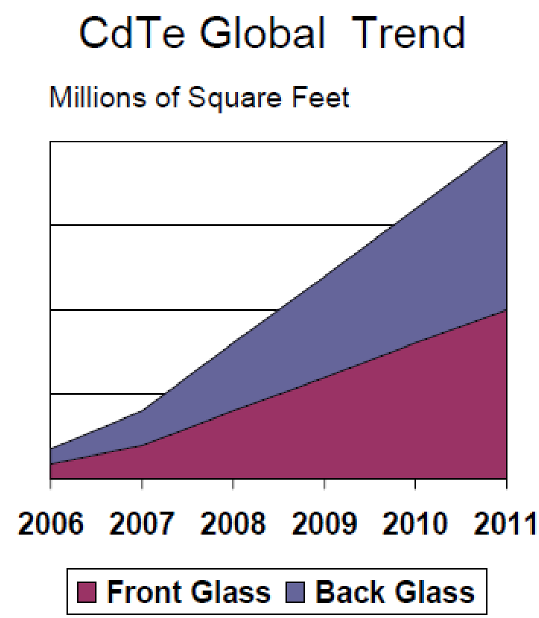
- Low iron containing materials drives up the cost to produce due to purchase price and freight costs from mines

Adapted from: Solar market impact on the glass industry, Jim West (Guardian Industries), International Workshop on Glass for Harvesting, Storage and Efficient Usage of Solar Energy, Nov. 16-18, 2008, Pittsburgh, PA

Thin Film CdTe PV Glass



Module Efficiency (%)	9-11
Wavelength range (nm)	400-900



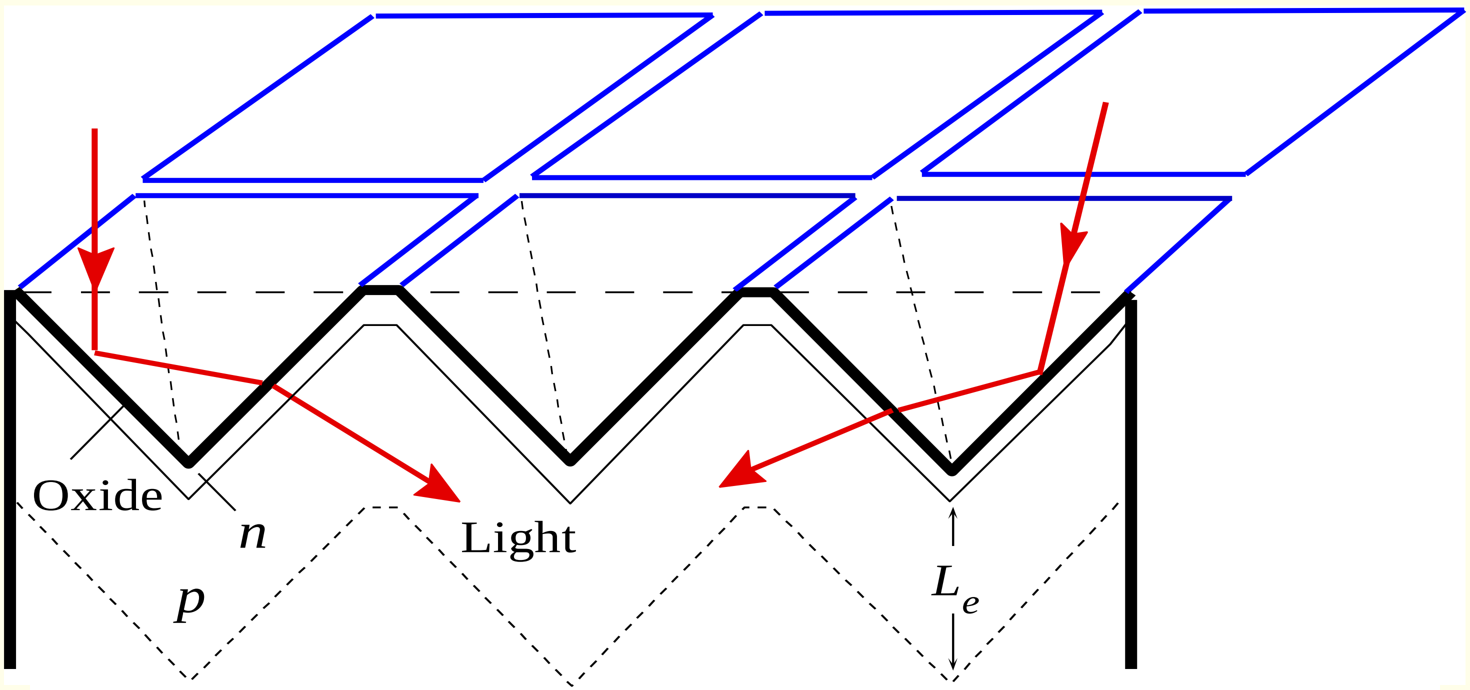
- CdTe benefits most from a low iron float glass: Tsolar > 90%
- Module transmission heavily impacted by TCO coating
- Back glass is standard clear float glass

Adapted from: Solar market impact on the glass industry, Jim West (Guardian Industries), International Workshop on Glass for Harvesting, Storage and Efficient Usage of Solar Energy, Nov. 16-18, 2008, Pittsburgh, PA

Minimizing reflection losses

Most solar cells use c-Si, with efficiencies from ~ 18% for polycrystalline Si, to 22-24 % for high efficiency single crystal devices. The best single c-Si homojunction solar cells have η ~ 24 %, like the PERL (passivated emitter rear locally) diffused cell, below.

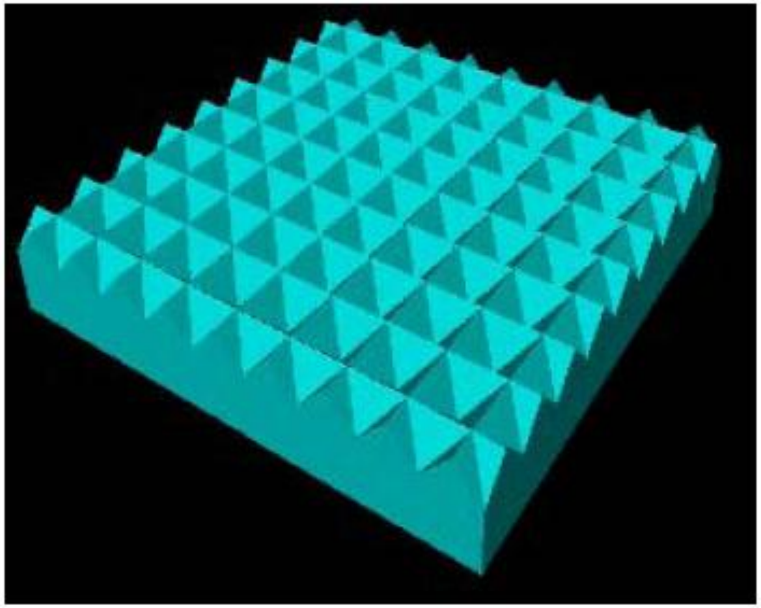
Glass covers in PV units can be patterned for enhanced light harvesting



Inverted pyramid textured surface substantially reduces reflection losses and increases absorption probability in the device

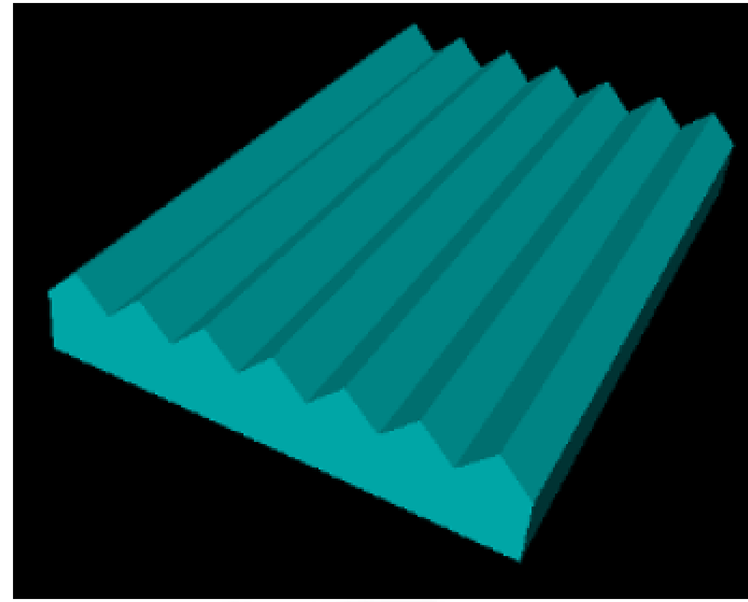
From: *Principles of Electronic Materials and Devices*, *Third Edition*, S.O. Kasap (© McGraw-Hill, 2005)

Minimizing reflection losses



Inverted Pyramids
(SGG Albarino P)

Best light-trapping



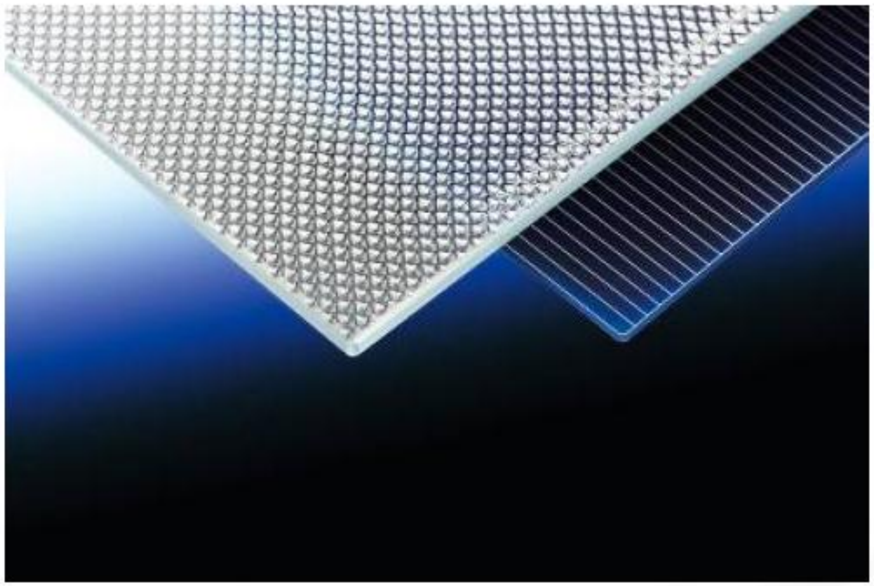
Grooves
(SGG Albarino G)

less sensitive to surface dust

with self-cleaning glass, only short-time dust accumulation

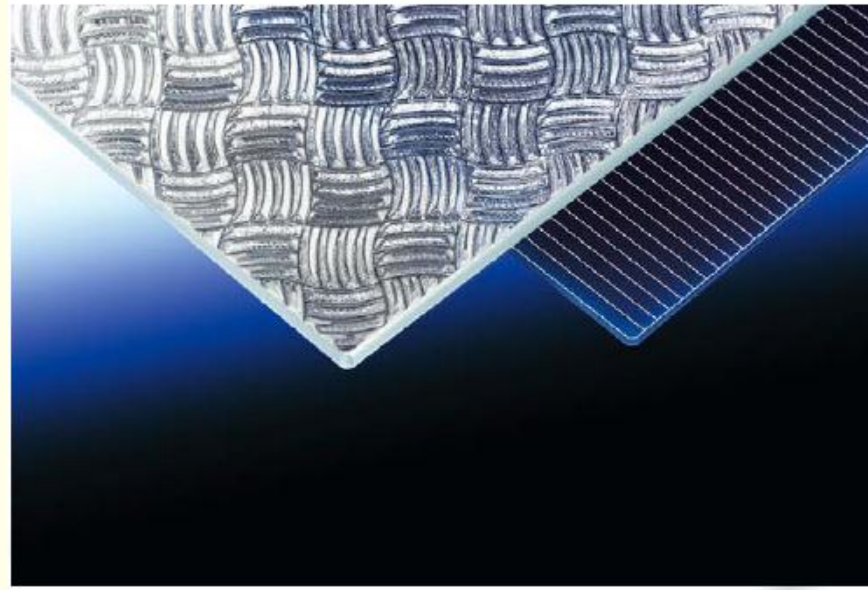
Adapted from: Sun-light harvesting with surface patterned glass for photovoltaics, Andreas Nositschka (Saint-Gobain Sekurit Deutschland), International Workshop on Glass for Harvesting, Storage and Efficient Usage of Solar Energy, Nov. 16-18, 2008, Pittsburgh, PA

Minimizing reflection losses



"randomized" pyramids

(SGG Albarino P)



curved grooves

(SGG Albarino G)

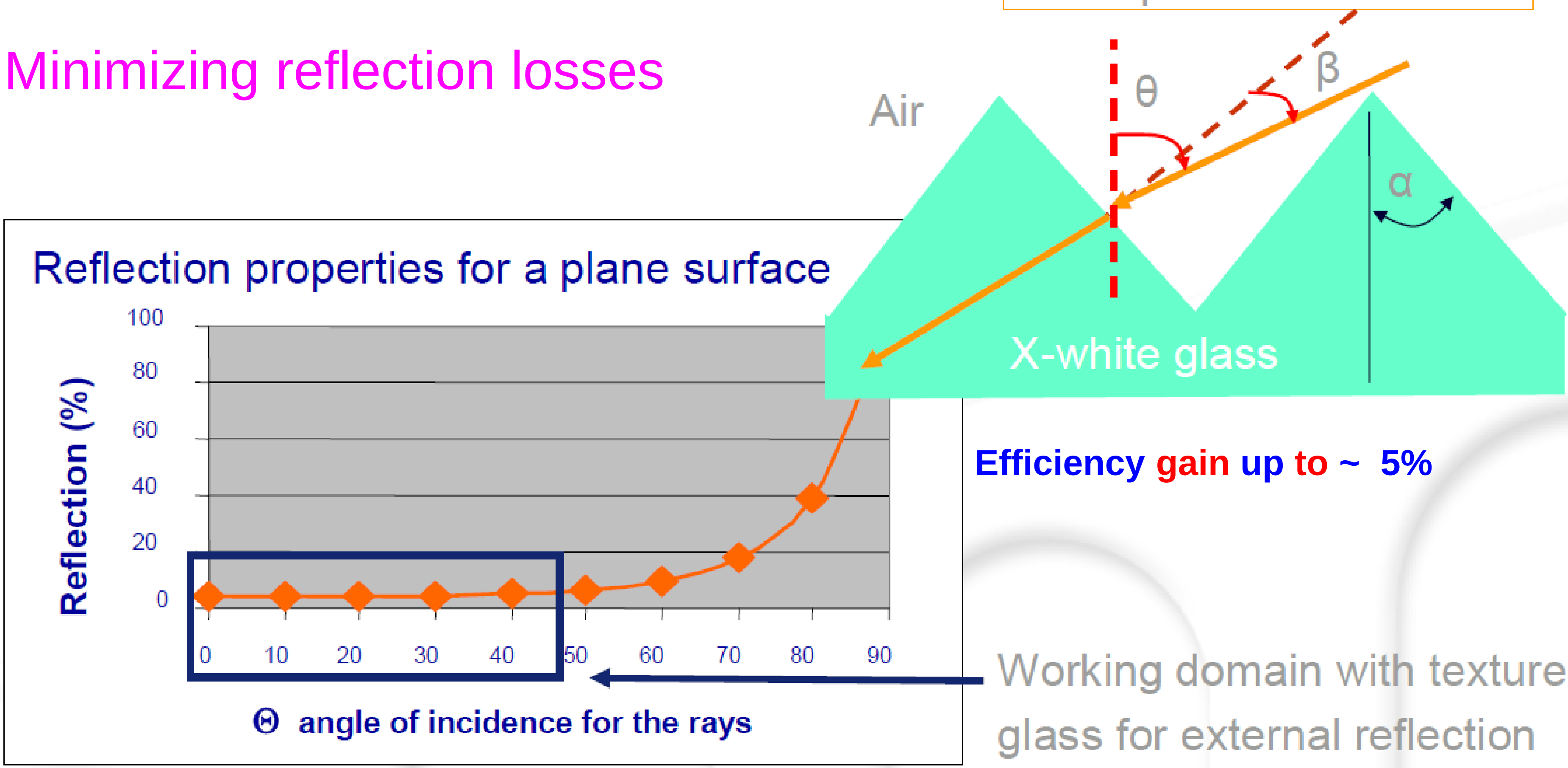
Adapted from: Sun-light harvesting with surface patterned glass for photovoltaics, Andreas Nositschka (Saint-Gobain Sekurit Deutschland), International Workshop on Glass for Harvesting, Storage and Efficient Usage of Solar Energy, Nov. 16-18, 2008, Pittsburgh, PA

SGGAlbarino P: Principle @ high angles of incidence

1. "Antireflective" effect : **lower reflection for flat angles**: R = 4 % @ 20º ; R = 13 % @ 65
(reduction of the angle of incidence of obliquely incident sun light**)**

For a texture : - 45°<β< 45° for α =45°

Minimizing reflection losses



Efficiency gain up to ~ 5%

Working domain with texture glass for external reflection

Adapted from: Sun-light harvesting with surface patterned glass for photovoltaics, Andreas Nositschka (Saint-Gobain Sekurit Deutschland), International Workshop on Glass for Harvesting, Storage and Efficient Usage of Solar Energy, Nov. 16-18, 2008, Pittsburgh, PA

Q.

Building Integrated Photovoltaics (BIPV): one of the fastest growing segments of PV

PPG IdeaScapes Glass • Coatings • Paint

Architectural glasses can be functionalized with encapsulated PV modules for façade or roofing.

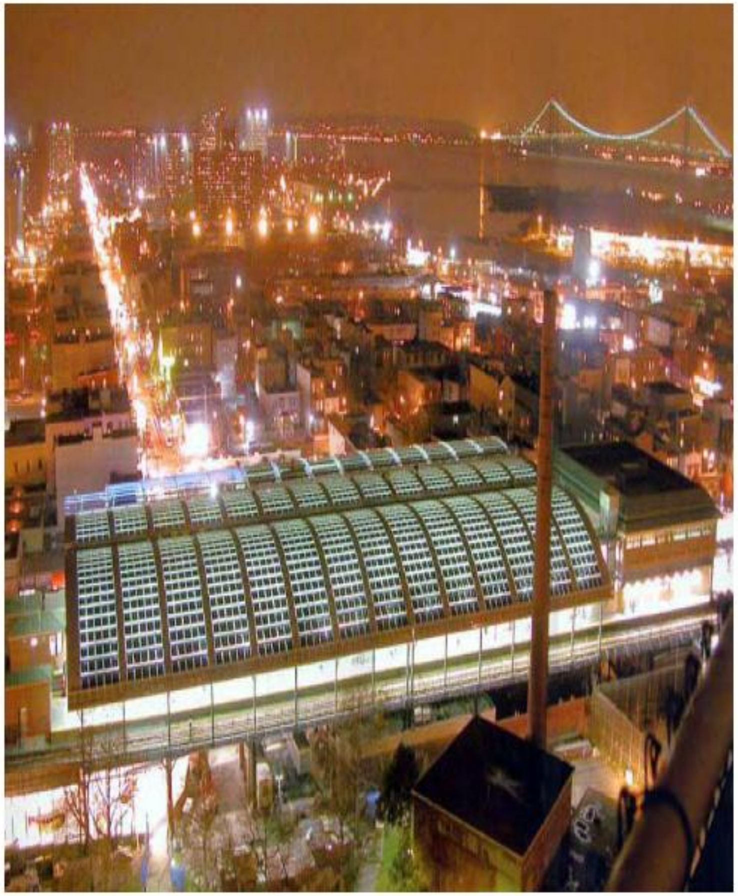
- •4,000+ square feet solar cells roof installation
- •Maximum theoretical output of 60 kilowatts

Renewable Energy: An Energy Destination for the West June 21-22, 2002

Adam Joseph Lewis Center for Environmental Studies
Oberlin College, Oberlin, Ohio

Adapted from: The future of High Performance Glazing in Commercial Buildings, James J. Finley (PPG Industries, Inc.), International Workshop on Glass for Harvesting, Storage and Efficient Usage of Solar Energy, Nov. 16-18, 2008, Pittsburgh, PA

Building Integrated Photovoltaics (BIPV)



Kiss + Cathcart, Architects

Coney Island's Stillwell Ave Terminal

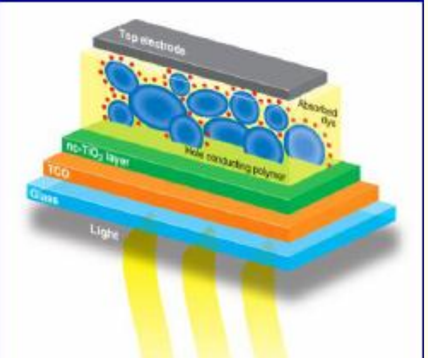
Kiss + Cathcart, Architects

the 2020 tower

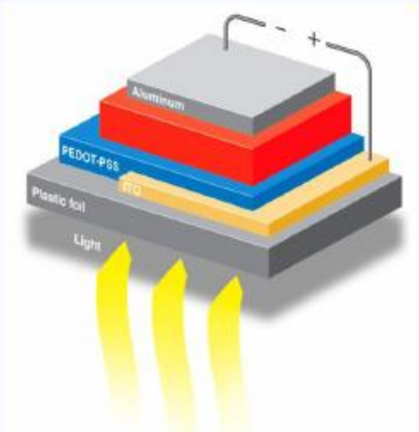
Adapted from: The future of High Performance Glazing in Commercial Buildings, James J. Finley (PPG Industries, Inc.), International Workshop on Glass for Harvesting, Storage and Efficient Usage of Solar Energy, Nov. 16-18, 2008, Pittsburgh, PA

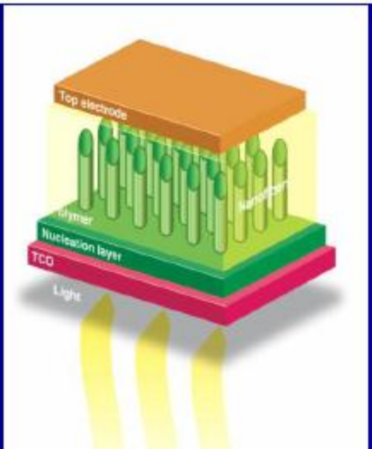
What are Excitonic Solar Cells? A wide range of possibilities!!

- Dye Sensitized Solar Cell (DSSC) on **glass** substrates
- Planar - Small Molecule
- Polymer - Fullerene Bulk Heterojunction
- Hybrid Polymer - Inorganic Ordered Bulk Heterojunction



DSSCs on glass substrates





Emerging technologies

Adapted from: The new challenges for photovoltaics as a long term reliable energy affordable resource, Rodrigo Martins (Cenimat, UNL), First IDS-FunMat Spring School, March 13-18, 2011, Sesimbra, Portugal

The *dye-sensitized solar cells*, based on mesoporous nanocrystalline anatase titania and an organic dye, offer a *possible cheaper alternative to PV cells*. Here, mesoporous titania is sensitized with a dye that absorbs much more sun light than pure titania, into the visible region, with the observed photovoltage probably resulting from a built-in potential at the back contact of the nanocrystalline film with the conducting glass, although a depletion layer cannot be formed because the particles are too small (~ 10 – 80 nm only).

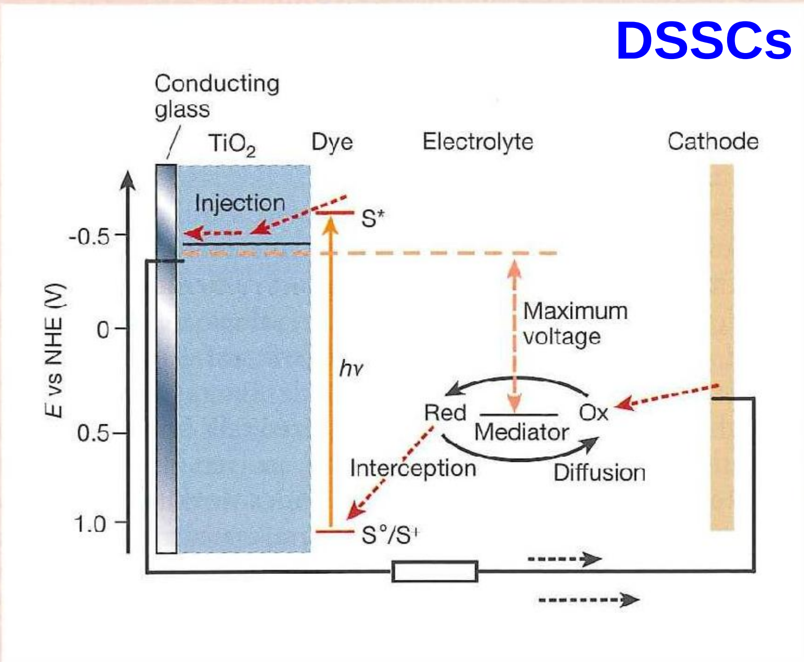


Figure 3 Schematic of operation of the dye-sensitized electrochemical photovoltaic cell. The photoanode, made of a mesoporous dye-sensitized semiconductor, receives electrons from the photo-excited dye which is thereby oxidized, and which in turn oxidizes the mediator, a redox species dissolved in the electrolyte. The mediator is regenerated by reduction at the cathode by the electrons circulated through the external circuit. Figure courtesy of P. Bonhôte/EPFL-LPI.

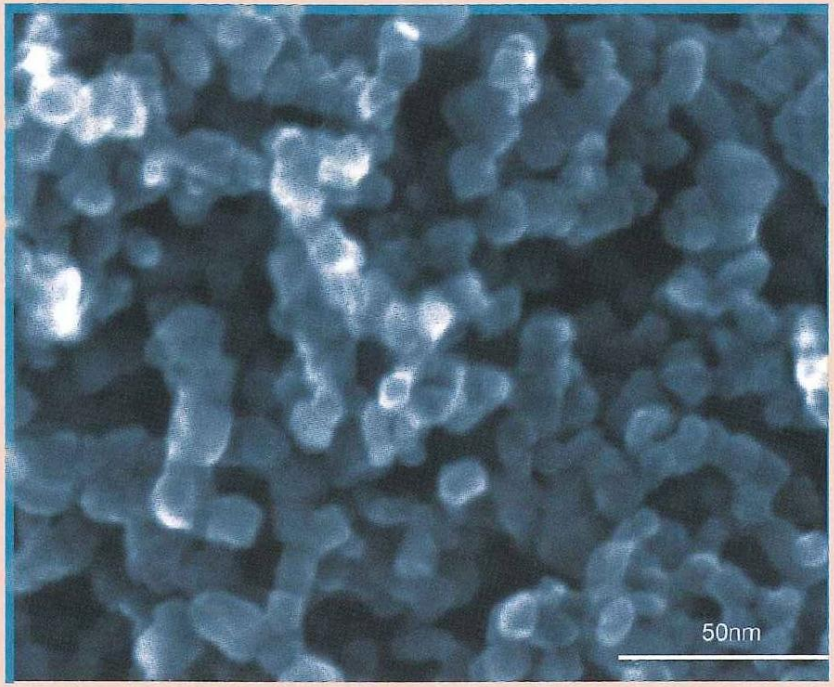


Figure 4 Scanning electron micrograph of the surface of a mesoporous anatase film prepared from a hydrothermally processed TiO_2 colloid. The exposed surface planes have mainly {101} orientation.

Adapted from: Michael Gratzel, Nature 414 (2001) 338 – 344.

Photocatalytic: self-cleaning glass

In semi-conducting **anatase titania**, light with energy above the bandgap (~ 3.2 eV) will create electron-hole pairs which catalyze the oxidation and decomposition of organic matter (including micro-organisms), thus having a self-cleaning effect. At the same time, photo-induced hidrophilicity also occurs, which provides anti-fogging behavior as well.

A thin film of nanocrystalline anatase (~ 15 – 20 nm thick) is usually grown on glass windows by CVD; in the laboratory, sol-gel processing has also been used to deposit such films.

Air borne, volatile, toxic or corrosive organic compounds effectively undergo photocatalytic oxidation, thus eliminating both indoor and outdoor pollution over the **self-cleaning**, titania-coated, **glass windows**.

One problem is that anatase titania, with a bandgap around 3.2 eV (386 nm), can only absorb UV light, a small fraction (~ 2 – 3%) of the solar energy. Therefore, newly developed catalysts are transition metal doped, e.g., taylored for the visible range also, increasing the efficiency of these products.

The Emerging Solar Market

- The solar market is growing at a rapid pace but will still need another 4-5 years to become a major glass market segment
- Glass production for solar has been dominated by low iron pattern glass for c-Si PV
- Thin film PV and CSP technologies will drive the demand and capacity increases in float assets; until volume is sizable it is difficult to dedicate float lines to the solar industry
- Based on current projections solar will be a viable market segment equal to residential, commercial, automotive, etc. in 2015
- The key sustaining the growth is the reduction in $ per watt

Adapted from: Solar market impact on the glass industry, Jim West (Guardian Industries), International Workshop on Glass for Harvesting, Storage and Efficient Usage of Solar Energy, Nov. 16-18, 2008, Pittsburgh, PA C

Questions?

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Photovoltaics

Concentrating Solar Power

Thermal – Hot Water

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