Solar modules



UNIK 4450/9450 – Schedule

- 30/8 Solar cell fundamentals
- 6/9 Solar cell efficiency
- 13/9 Semiconductor theory
- 20/9 Generation
- 27/9 Recombination and lifetime
- 4/10 Silicon
- 11/10 Junctions
- 18/10 Solar cells
- 25/10 Silicon solar cells I (@IFE)
- 1/11 Silicon solar cells II
- 8/11 Alternative solar cells
- 15/11 Light trapping
- 22/11 Cancelled
- 29/11 Solar modules + Q&A
- 6/12 Short Q&A (optional)

- Oral exam December 12th

Overview

- Solar module requirements
- Making Si solar modules
- Solar module performance

Solar module requirements

Solar module requirements

- A solar module must
  - Protect against mechanical damage
    - Si cells are fragile and brittle
    - Hail, thrown, fallen or landing objects (birds, UFOs…)
    - Sandstorms
  - Supply chemical protection
    - Corrosion of metallic contacts and cell interconnects must be avoided
  - Supply electrical insulation
    - A range of systems with voltages from 10 V to well over 1000 V
  - Supply UV protection
    - Polymers are prone to photochemical degradation

Solar module requirements

- A solar module must
  - Have good tolerance over a large temperature range
    - Winter temperatures can be well below -30 ^{o}C in Norway
    - Module temperatures can exceed 60 ^{o}C in the summer
  - Maintain as low a cell temperature as possible
    - Solar cell efficiency a function of temperature
  - Be self-cleaning
  - Ensure reliable solar cell operation for the entire solar module lifetime
    - Lifetime should preferably exceed 20 years

  - … AND still be inexpensive!

Standards

- Standards generally used in photovoltaic panels:
  - IEC 61215 (crystalline silicon performance), 61646 (thin film performance) and 61730 (all modules, safety)
  - ISO 9488 Solar energy—Vocabulary.
  - UL 1703 From Underwriters Laboratories
  - UL 1741 From Underwriters Laboratories
  - UL 2703 From Underwriters Laboratories
  - CE mark
  - Electrical Safety Tester (EST) Series (EST-460, EST-22V, EST-22H, EST-110).

Solar module zoology

- Rooftop modules for residential applications
- Solar modules for iPODs, calculators, toys…
- Flexible modules
- Transparent modules
- Building-integrated modules
- Concentrator modules
- Modules for extraterrestrial applications
- Efficient solar modules
- Inexpensive solar modules
- Artsy solar modules
- Large modules and tiny modules
- …

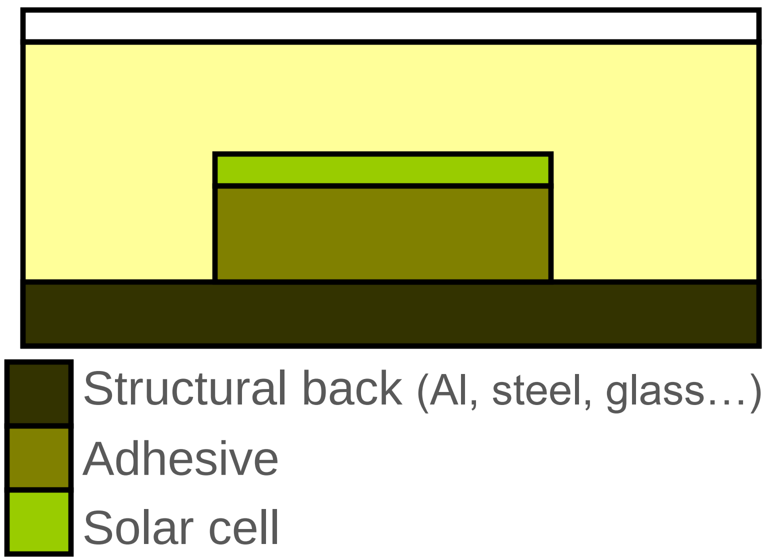
Si solar module strategies

- Use a structural layer to provide rigidity
  - Structural front configuration
  - Structural back configuration
- Encapsulate the solar cells to ensure chemical resistance
  - Potting layer
  - Laminate
- Use a transparent top layer that supplies resistance to mechanical damage and UV radiation and is self-cleaning
  - Glass
- Include sufficient moisture barriers

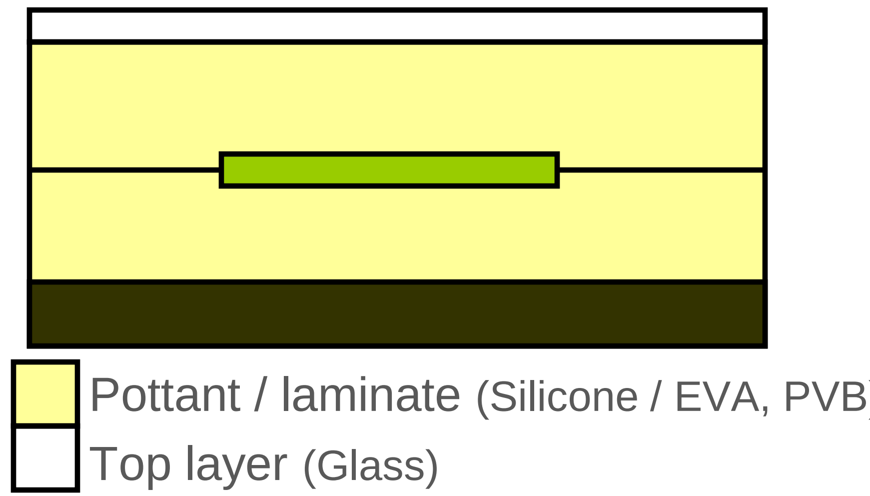
Making Si solar modules

Structural back

With pottant

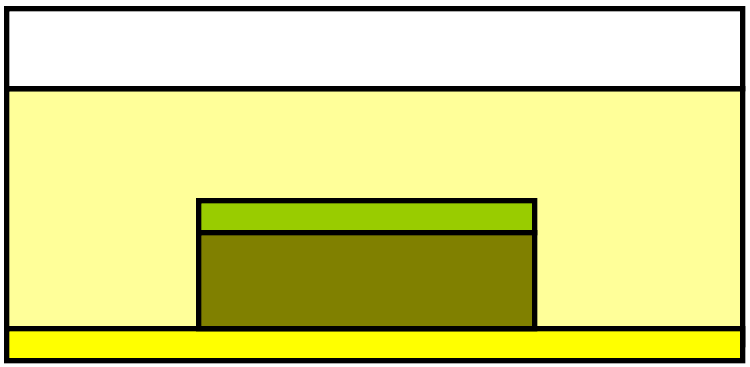


With laminate

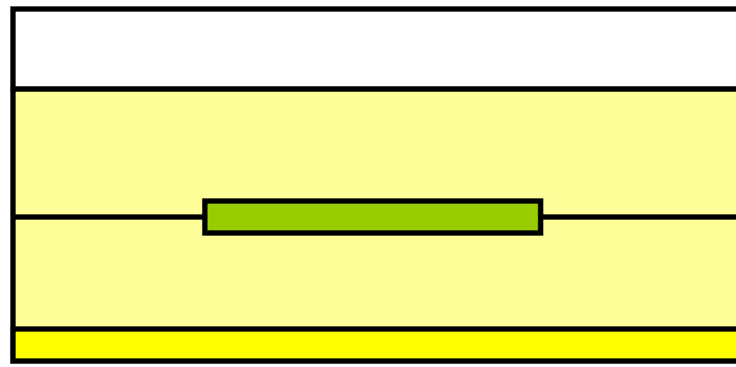


Structural front

With pottant



With laminate



- Adhesive
- Solar cell
- Back layer (Mylar, Tedlar, sometimes with extra moisture barrier layer)

- Pottant / laminate (Silicone / EVA, PVB)
- Structural top layer (Glass)

Glass

- Tempered glass with low iron content is often used
  - High transmittance from 350 to 1200 nm
  - Cheap
  - Strong
  - Stable
  - Good self-cleaning properties

Glass applications in solar modules

- Cover glass on the solar module front
- Substrate glass on the solar module rear
- Examples:
  - Wafer-based solar panels often only utilize cover glass, rear is protected using other materials
  - Thin film solar cells are often grown on glass substrates
  - In some cases, the glass acts as both a cover and substrate glass

Glass applications in solar modules

Cover glass

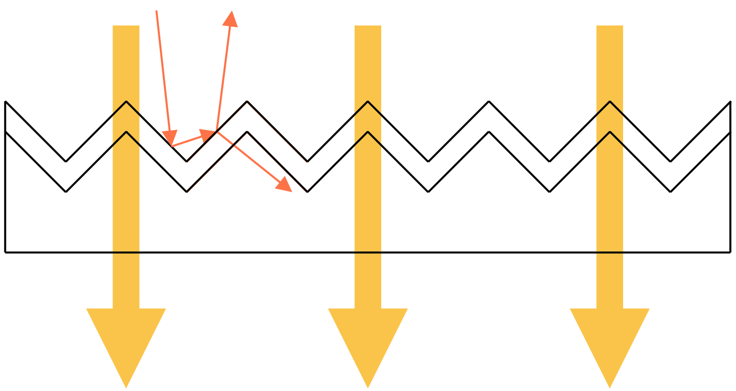
- Roles:
  - Supply protection towards external forces and the elements
  - Hinder current generation as little as possible
- Requirements:
  - Transparent
  - Low reflectance
  - Mechanical protection
  - Self-cleaning
  - UV-protection (in some cases)

Substrate glass

- Roles:
  - Be a suitable substrate for solar cell deposition atop the glass
  - In certain cases enhance cell absorption through texturing
- Requirements:
  - Support deposition processes of high quality solar cell materials
    - Temperature requirements
    - Be chemically inert or interact beneficially with the deposition process

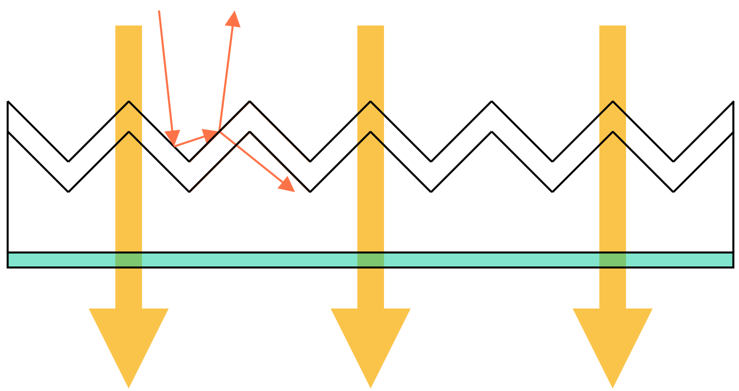
Cover glass

- Transparency
  - Low-iron content in glass
  - Depending on underlying module layers, some absorption in ÙV-range can be beneficial
- Reflectance
  - Refractive index
  - Anti-reflection coatings
  - Textures



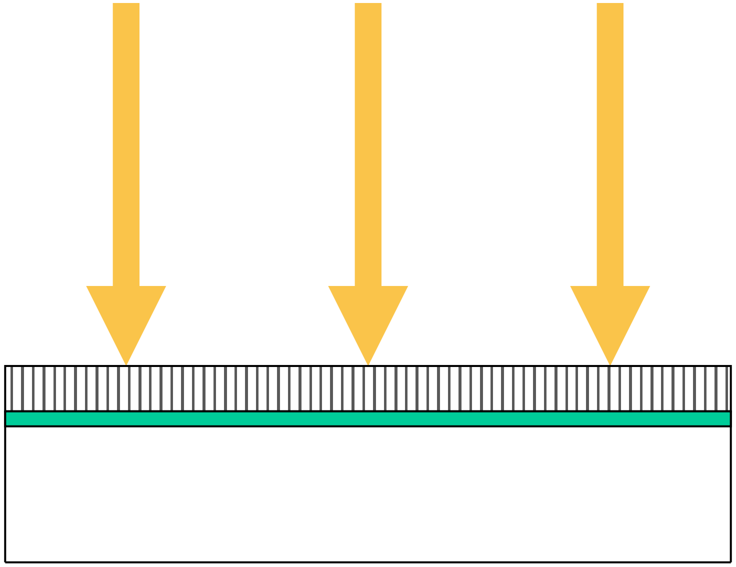
Cover glass

- Additional requirements
  - Front contacts
    - Transparent conductive oxides
- Other properties
  - Self-cleaning
  - Mechanical protection



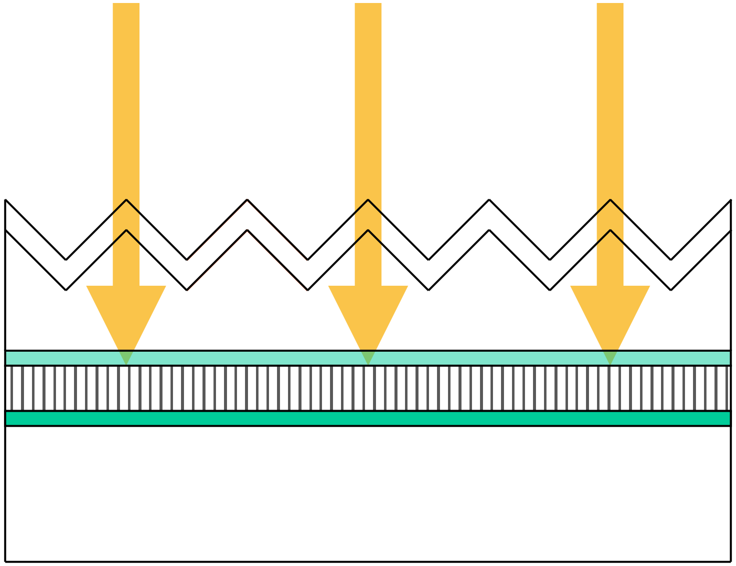
Substrate glass

- Process compatibility
  - Glass must support the deposition of high-quality solar cell materials
    - Chemical inertness
    - Beneficial chemical interactions
    - Process temperature windows
- Additional requirements
  - Rear contacts
    - Metal deposition
  - Transmittance reduction
    - Textured substrates
    - Rear reflectors



Additional comments

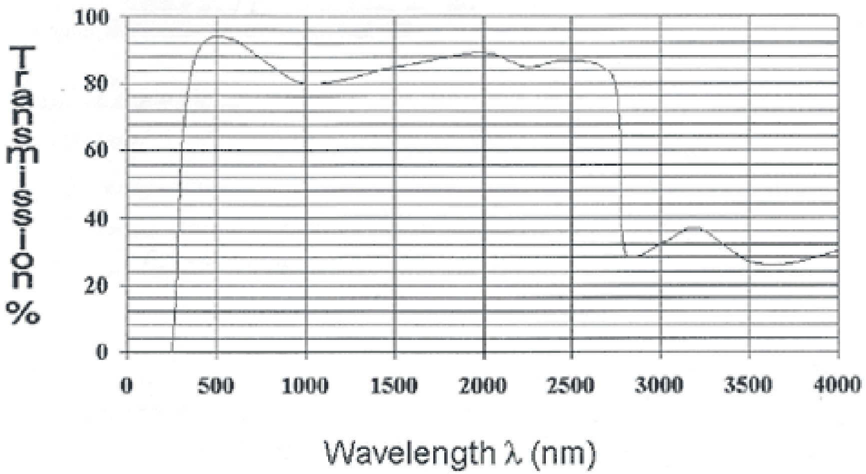
- Several solar modules contain two glass plates
- Bifacial modules can be interesting for several applications



Commonly used glass types

- Most used type of glass in general
- Relatively inexpensive
- Softening temperature: ~725 ^{o}C
- Density: ~2.5 g/cm^3
- Refractive index (n): ~1.52
- Transmission: <90%
- Moderate dispersion

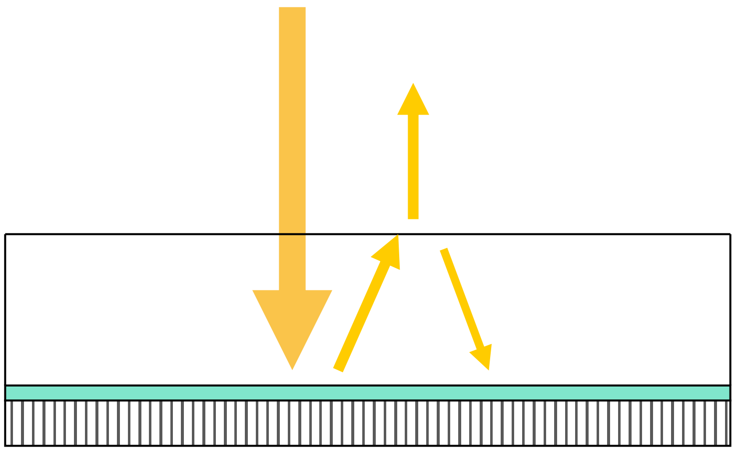
Soda Lime / AR / Flint Glass



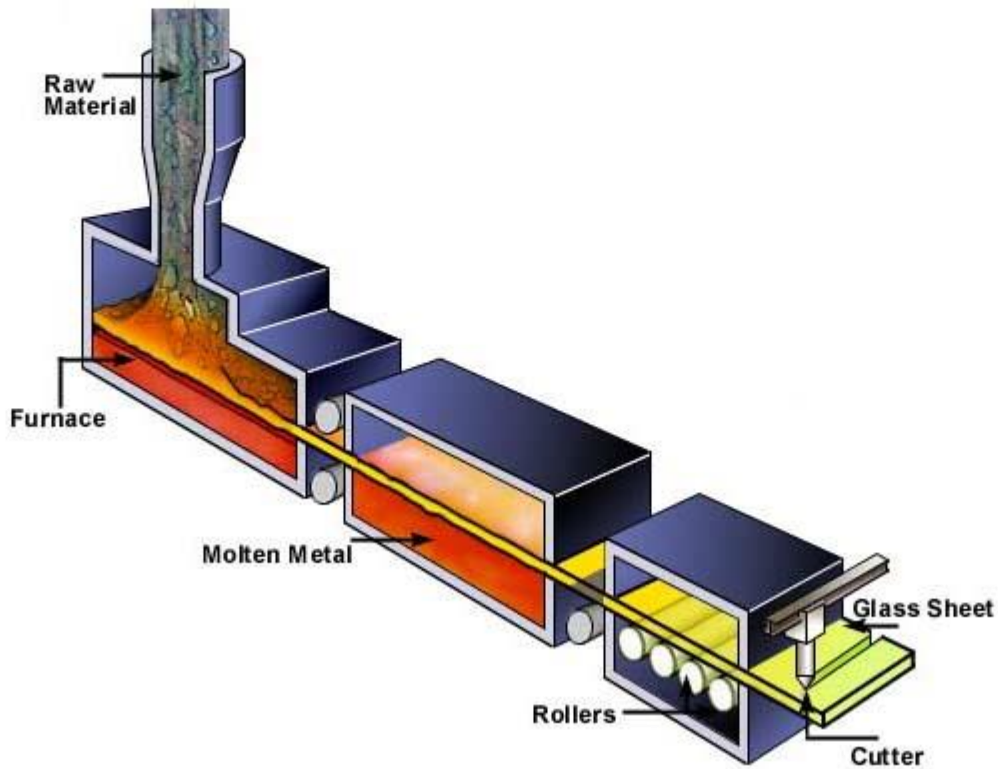
Source: Corning, wikipedia

Overall transmittance

- The total transmitted light into the solar cell is partly determined by
  1. The glass material
  2. Any other intermediate layer (laminates, thicker TCO films…)
  3. The complex interplay between light reflected from the cell back into the glass, and back again through (total) internal reflection
- Angular dependence of the overall transmittance an important factor
- Ray tracing a good predictive tool for this purpose



Making glass



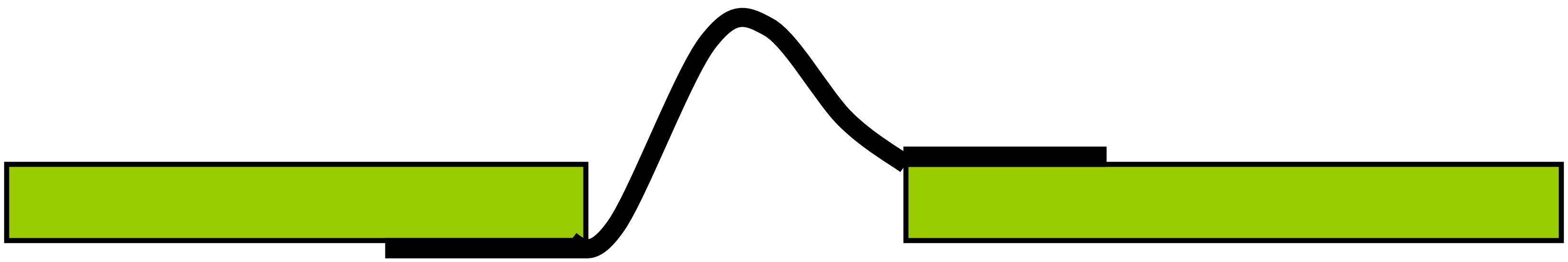
Wisedude.com

Laminate

- UV-resistant laminates are now in common use
  - EVA
  - PVB

Cell interconnects

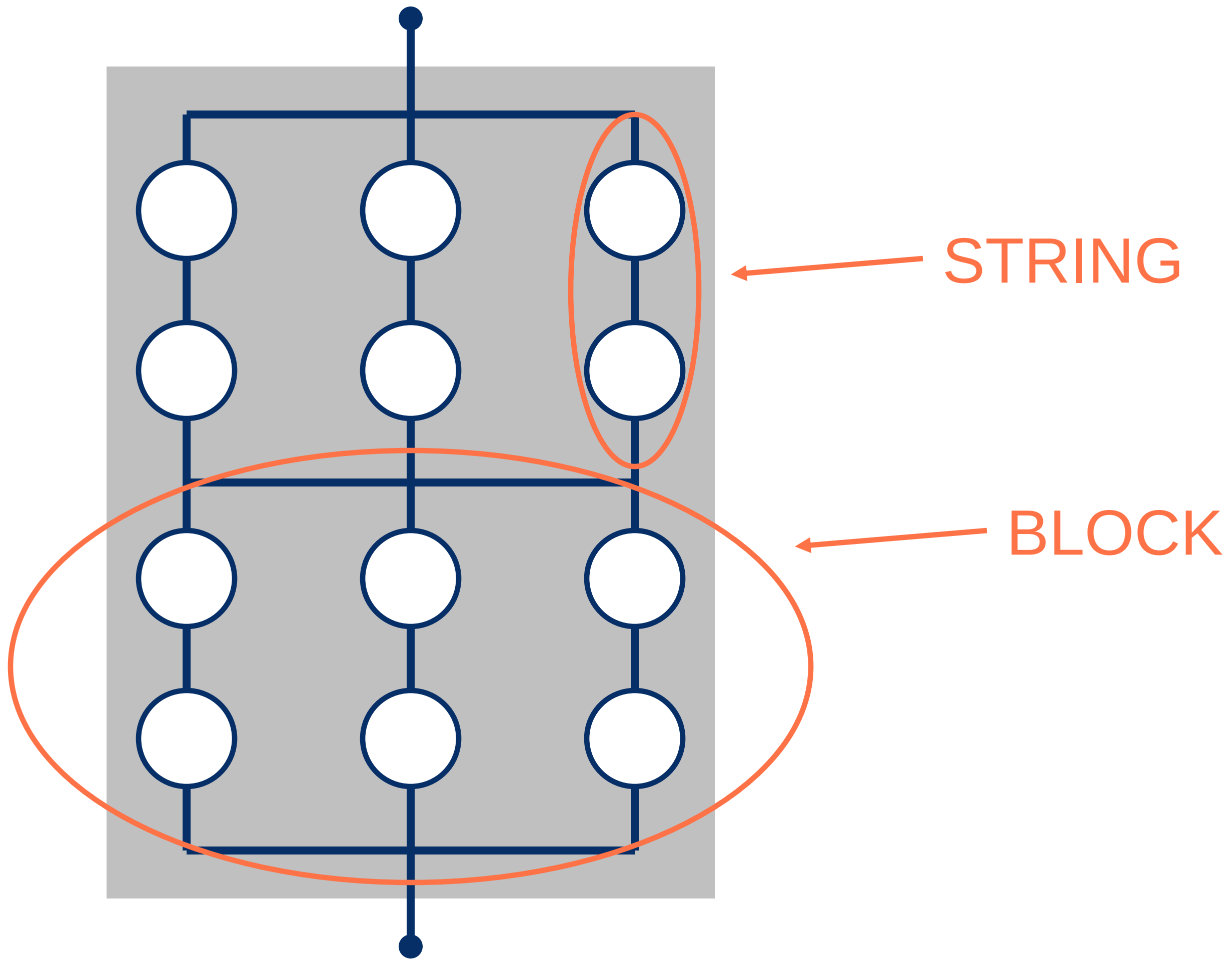
- The cells are interconnected using metal strips
  - Interconnects include stress-relief loops to reduces the impact of thermal expansion during thermal cycling



Module circuit design

- The solar cells in a solar module are connected in the following way
  - Series connected for desired V
    - The output V becomes the sum of the independent output V of the solar cells in a string
    - Output V per cell typically around 0.5 V
  - Parallel connected for desired I
    - The output I becomes the output I of one cell multiplied with the number of strings
    - Output current per solar cell area typically 30 mA/cm^2

Module circuit design

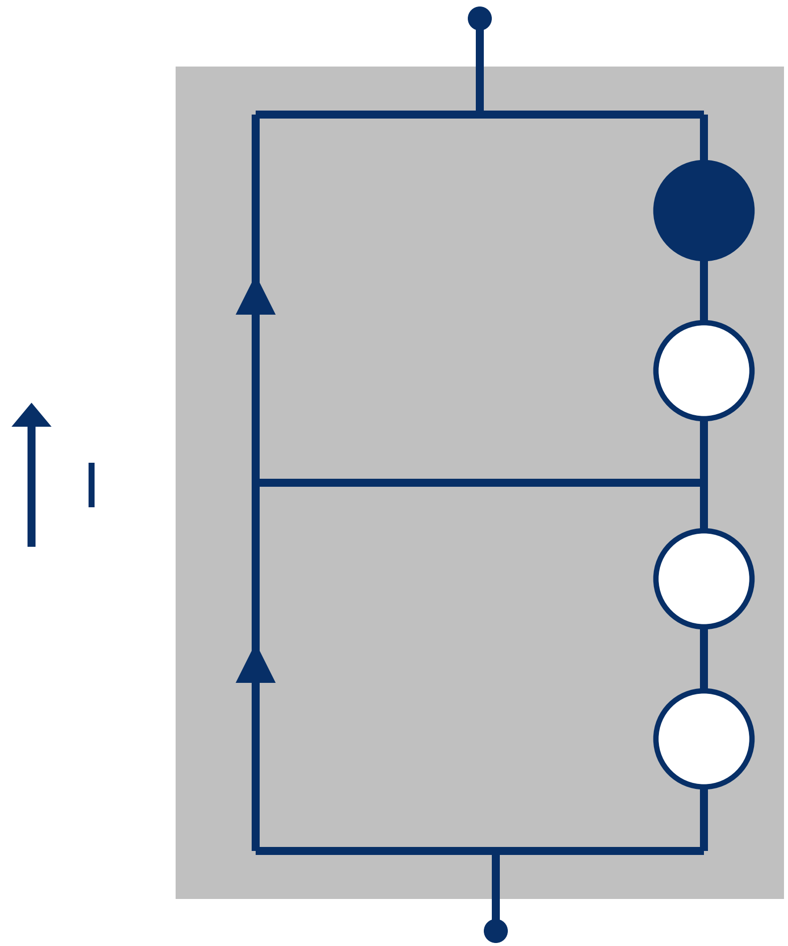


Module circuit design

- If solar cells are not equal and/or recieve equal irradiation
  - Cell mismatch losses
  - Shaded or damaged cells will degrade module performance
  - Worst case: shaded or poor cells might become reverse biased
  - Local hot-spots formed on cell might destroy cell!

- Hot-spots can be avoided by using bypass diodes
  - Become forward biased when block becomes reverse biased
  - However: one diode per cell is too expensive…

Bypass diodes



Solar module performance

Solar module performance

- Effect of irradiance (G)

$$J_{SC}(G) \sim (J_{SC,ref}/G_{ref}) \cdot G$$

- Effect of temperature

$$V_{OC}(T_c) = V_{OC,ref} + (T_c - T_{c,ref}) \cdot (dV_{OC}(T)/dT)$$

Power temperature coefficient

Technology	dP_{max}/dT [%/K]
Crystalline Si	From -0,25 to -0,55
Amorphous Si	From -0,05 to -0,20
CdTe	From -0,15 to 0,40
CIGS	From -0,25 to –0,65

Power temperature coefficient

- The efficiency of a solar cell depends on the solar cell operating temperature (T_c)
  - Efficiency reduced as T_c increases
- For a given set of conditions, T_c is different for different module designs
- The nominal operating cell temperature (NOCT) is an important module parameter!

NOCT

- Nominal operating cell temperature (NOCT)
  - Different module designs result in different cell termperatures during operation
  - Cell performance decreases as temperature increases
  - Defined for a set of standard testing conditions (STC)
    - G_{ref} = 800 W/m^2
    - Wind speed 1 m/s
    - Ambient temperature = 20 ^{o}C
    - Mounting: open back side
  - Typical NOCT between 40 and 50 ^{o}C

NOCT

- The cell temperature during operation is given by

$$T_c = T_a + (NOCT(^oC) - 20) \cdot (G/G_{ref})$$

Degradation and failure modes

- Typical solar module failure modes
  - Cells
    - Breakage due to thermal fluctuations, hail, vandalism
    - Contact corrosion
    - ARC deterioration
  - Interconnects
    - Open circuits due to inadequate stress relief
    - Interconnect corrosion

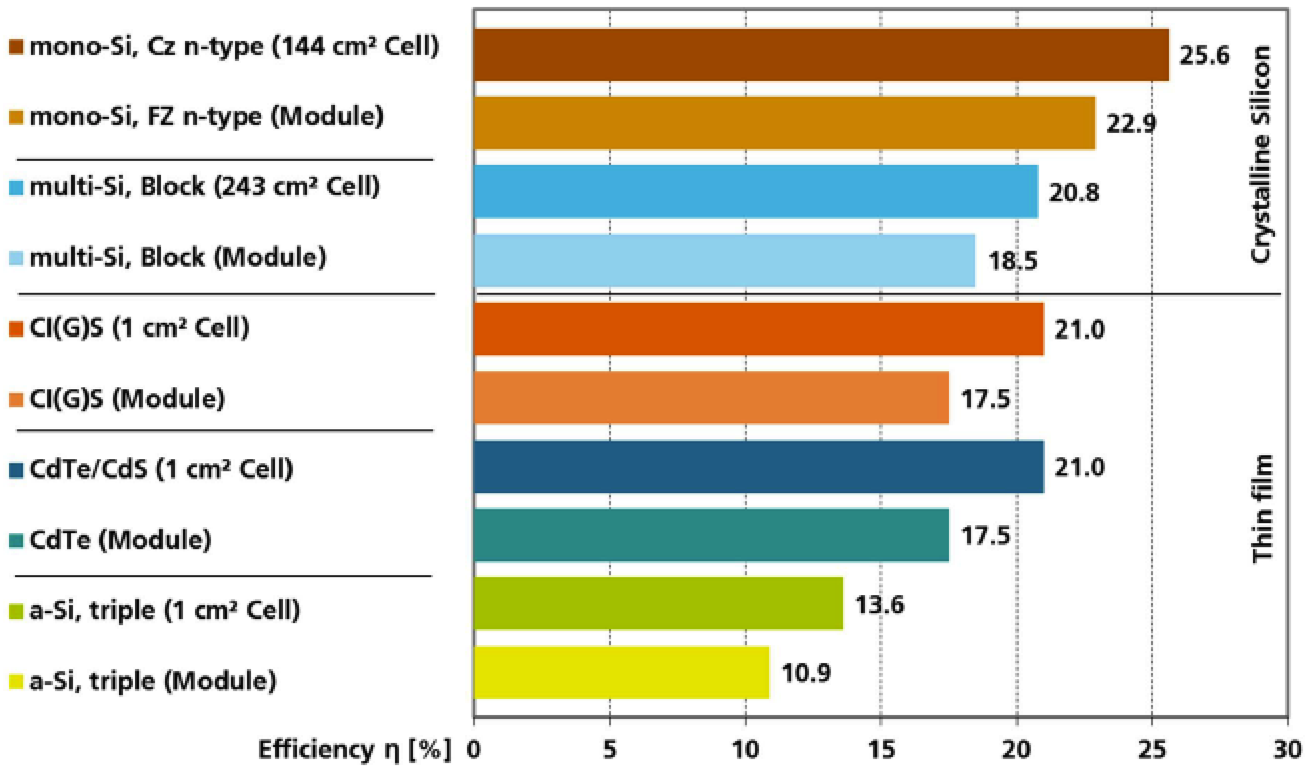
Degradation and failure modes

- Typical solar module failure modes
  - Encapsulant
    - Delamination of encapsulation
    - Discoloring of encapsulant due to UV exposure, temperature or humidity
    - Browning of EVA and build-up of acetic acid
  - Dirt accumulation on surface
    - Can reduce output by up to 10 % (only!) when glass is used
  - Hot-spots

Lifetime tests

- In order to ensure that module designs result in long module lifetimes, modules are tested
  - Field testing
    - Best (realistic!)
    - Time consuming
  - Accelerated (laboratory) testing
    - Thermal cycling
    - Humidity
    - Prolonged UV radiation
    - Cyclic pressure loading
  - A Si module typically has a lifetime well in excess of 20 years

Efficiency Comparison of Technologies:
Best Lab Cells vs. Best Lab Modules

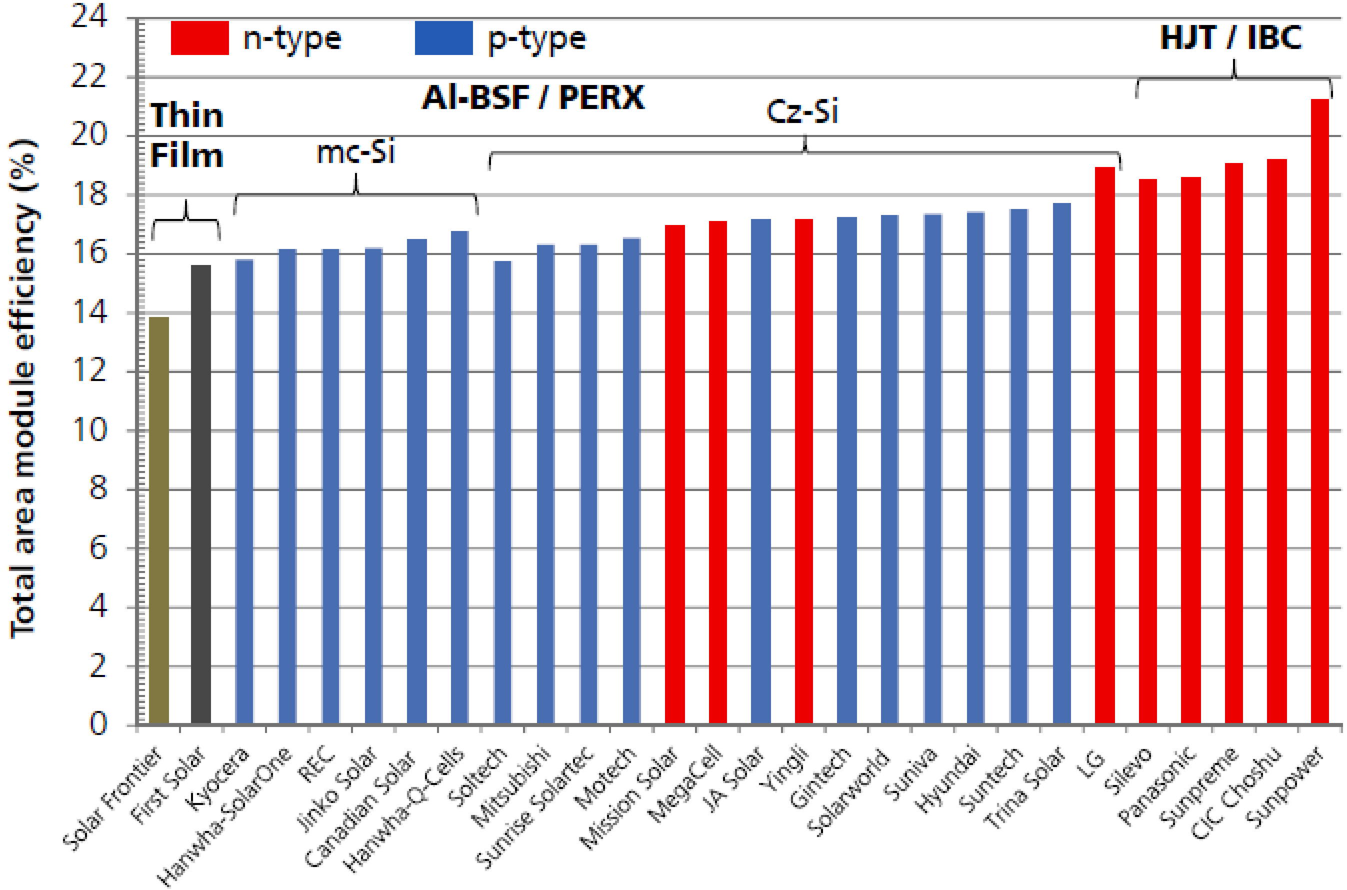


Data: Green et al.: Solar Cell Efficiency Tables,(Version 46), Progress in PV: Research and Applications 2015. Graph: PSE AG 2015

Fraunhofer ISE

Current Efficiencies of Selected Commercial PV Modules

Sorted by Bulk Material, Cell Concept and Efficiency



Note: Exemplary overview without claim to completeness; Selection is primarily based on modules with highest efficiency of their class and proprietary cell concepts produced by vertically integrated PV cell and module manufacturers; Graph: Jochen Rentsch, Fraunhofer ISE. Source: Company product data sheets. Last update: Nov. 2015.

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15.8% EFFICIENCY

10 YEAR PRODUCT WARRANTY

25 YEAR LINEAR POWER OUTPUT WARRANTY

TEMPERATURE RATINGS

Nominal Operating Cell Temperature (NOCT)	45.7°C (±2°C)
Temperature Coefficient of P_{MPP}	-0.40 %/°C
Temperature Coefficient of V_{OC}	-0.27 %/°C
Temperature Coefficient of I_{SC}	0.024 %/°C

GENERAL DATA

Cell Type:	60 REC PE multi-crystalline 3 strings of 20 cells
Glass:	3.2 mm solar glass with anti-reflection surface treatment
Back Sheet:	Double layer highly resistant polyester
Frame:	Anodized aluminium (silver)
Junction Box Design 1:	Huber & Suhner: IP67 rated 3 bypass diodes 4 mm² solar cable, 0.9 m + 1.2 m Radox 4 mm², twist lock connectors
Junction Box Design 2:	Hosiden: IP67 rated 4 bypass diodes 4 mm² solar cable, 0.9 m + 1.2 m Hosiden 4 mm² connectors, MC4 connectable

MAXIMUM RATINGS

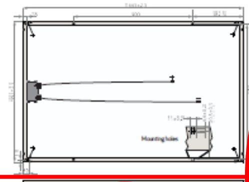
Operational Temperature:	-40 ... +80°C
Maximum System Voltage:	1000 V
Maximum Snow Load:	550 kg/m² (5400 Pa)
Maximum Wind Load:	244 kg/m² (2400 Pa)
Max Series Fuse Rating:	25 A
Max Reverse Current:	25 A

MECHANICAL DATA

Dimensions:	1665 x 991 x 38 mm
Area:	1.65 m²
Weight:	18 kg

Note! Specifications subject to change without notice.

REC PEAK ENERGY SERIES



ELECTRICAL DATA @ STC

ELECTRICAL DATA @ STC	REC235PE	REC240PE	REC245PE	REC250PE	REC255PE	REC260PE
Nominal Power - P_{MPP} (Wp)	235	240	245	250	255	260
Watt Class Sorting - (W)	0/+5	0/+5	0/+5	0/+5	0/+5	0/+5
Nominal Power Voltage - V_{MPP} (V)	29.5	29.7	30.1	30.2	30.5	30.7
Nominal Power Current - I_{MPP} (A)	8.06	8.17	8.23	8.30	8.42	8.50
Open Circuit Voltage - V_{OC} (V)	36.6	36.8	37.1	37.4	37.6	37.8
Short Circuit Current - I_{SC} (A)	8.66	8.75	8.80	8.86	8.95	9.01
Module Efficiency (%)	14.2	14.5	14.8	15.1	15.5	15.8

Analysed data demonstrates that 99.7% of modules produced have current and voltage tolerance of ±3% from nominal values.
Values at standard test conditions STC (airmass AM 1.5, irradiance 1000 W/m², cell temperature 25°C).
At low irradiance of 200 W/m² (AM 1.5 and cell temperature 25°C) at least 97% of the STC module efficiency will be achieved.

ELECTRICAL DATA @ NOCT

ELECTRICAL DATA @ NOCT	REC235PE	REC240PE	REC245PE	REC250PE	REC255PE	REC260PE
Nominal Power - P_{MPP} (Wp)	179	183	187	189	193	197
Nominal Power Voltage - V_{MPP} (V)	27.5	27.7	28.1	28.3	28.5	29.0
Nominal Power Current - I_{MPP} (A)	6.51	6.58	6.64	6.68	6.77	6.81
Open Circuit Voltage - V_{OC} (V)	34.2	34.4	34.7	35.0	35.3	35.7
Short Circuit Current - I_{SC} (A)	6.96	7.03	7.08	7.12	7.21	7.24

Nominal cell operating temperature NOCT (800 W/m², AM 1.5, windspeed 1 m/s, ambient temperature 20°C)

CERTIFICATION

IEC 61215 & IEC 61730, IEC 62716 (ammonia resistance) & IEC 61701 (salt mist - severity level 6)

Member of PV Cycle

WARRANTY

10 year product warranty
25 year linear power output warranty
(max. degression in performance of 0.7% p.a.)