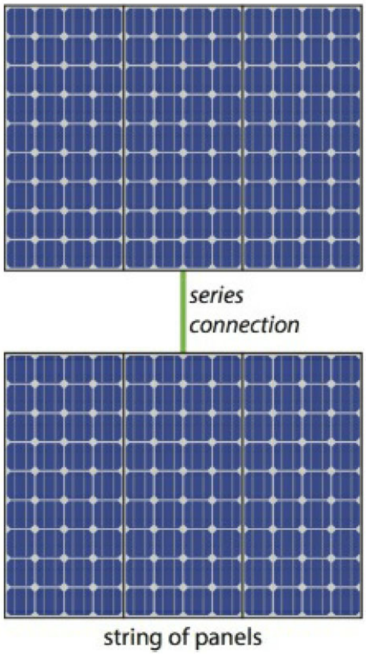
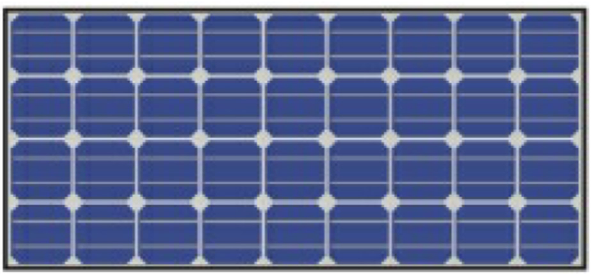
Photovoltaic Module Terminology

- Start with c-Si solar cells
- PV module (also PV panel, solar panel) $\Rightarrow$ many solar cells are electrically connected together
- PV array $\Rightarrow$ consists of several solar panels, e.g. one strings of two PV panels each, where string means that these panels are connected in series

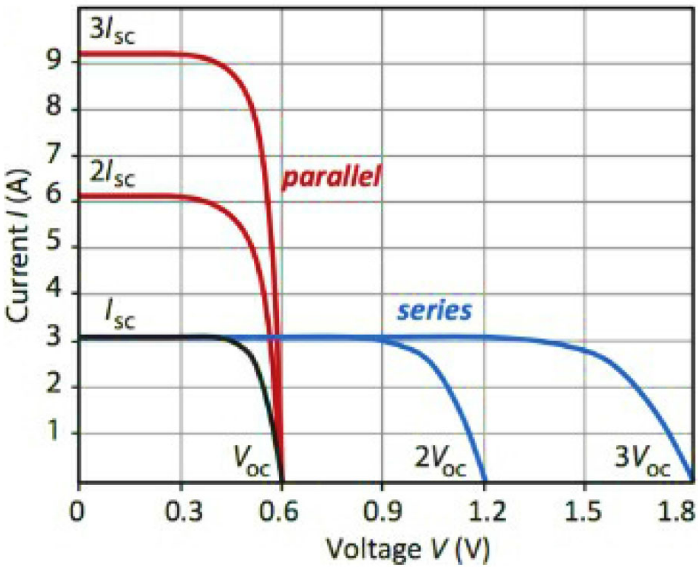


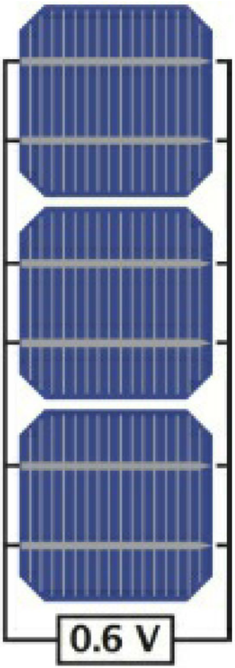


Source: textbook

Series and Parallel Connections

- Solar cells can also be connected in parallel ⇒ voltage is same over all solar cells, while currents of solar cells add up
- Demonstrated graphically: I-V curve of solar cells connected:
  - in series
  - in parallel





Source: textbook

PV Module Parameters

- In general, I-V characteristics of PV module consist of *m* identical cells in series and *n* identical strings in parallel
- Most common parameters are V_{oc}, I_{sc} and *FF*
- Total module area = aperture area + dead area

"Aperture area" is the area of the solar cells

"Dead area" consists of space in between solar cells and around edges of PV module

PV Module Parameters

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- Ideal world $\Rightarrow$ perfectly-matched solar cells $\Rightarrow$ no losses $\Rightarrow$ η and FF same at both cell and module level to be same…

  … but not the case in real life:

  1) the interconnects between cells incur further resistive losses

  2) there are small mismatches between interconnected cells
- When $m \times n$ cells are interconnected $\Rightarrow$ cell with lowest current in a string of *m* cells in series determines the module current
- Mismatch between individual cells caused by slight variations in production process
- In practice, PV modules perform slightly worse than one would expect from ideally matched and interconnected solar cells, i.e. PV module η lower by 2-3% absolute compared to cell η

PV Module Parameters

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HIT® photovoltaic module

SANYO

R&D technology adaptation

Improvement of the cell efficiency to reduce
- Carrier recombination loss
- Optical absorption loss
- Resistance loss

New tab design

Three tabs application
- Reducing electrical loss between the cell fingers and tabs
- Making the tab width thinner to expand the light receiving surface

Anti-reflection glass

Light capturing technology
- Reducing reflection and scattering of incoming light
- Improving generated electricity levels in morning and evening times

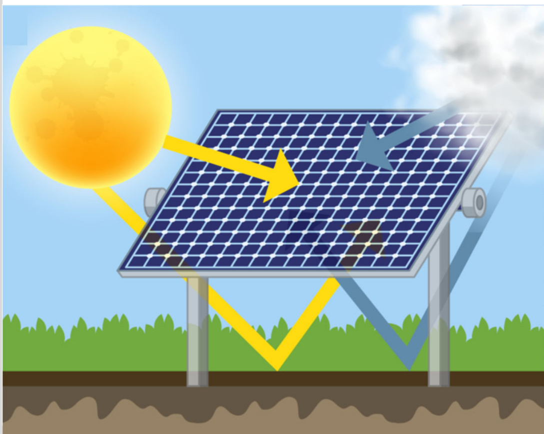
19.0%*
190 W/m²

HIT-N240SE10
HIT-N235SE10
HIT-N230SE10

Source: http://www.solaruk.com/pdf/DS%20-%20HIT235%20-%20HIT%20235%20SE10%20-%20datasheet.pdf

Bifacial PV Modules

- Bifacial ≡ two faces ⇒ PV module designed to accept light from both front and rear
- Both front & rear must be optically transparent
  ⇒ typically glass-glass structure
- ~10-25% gain via albedo – light reflected from ground an onto rear side of PV module

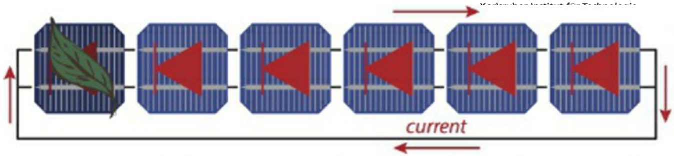


Source: https://www.trace-software.com/blog/bifacial-solar-panels-characteristics-and-advantages/

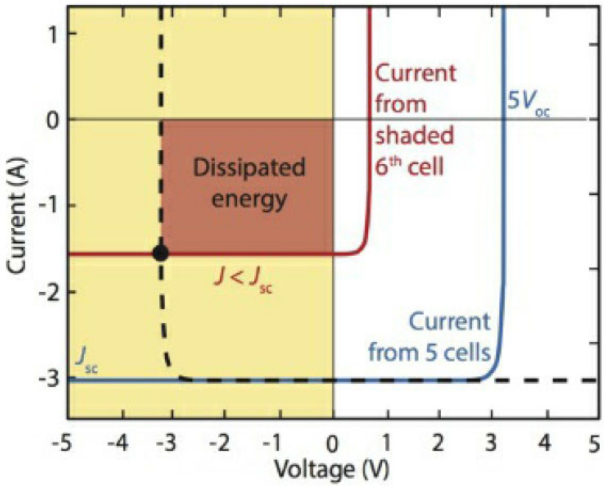
Partially Shaded PV Modules

Bypass Diodes

- Shaded solar cell generates much less photocurrent

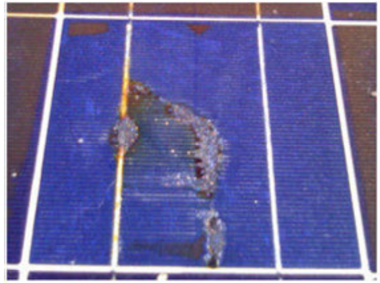


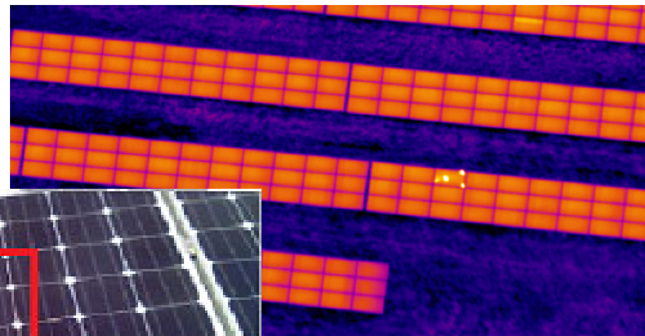
- 5 unshaded cells ⇒ acts like reverse bias on shaded solar cell
- When a cell is reverse biased ⇒ cannot generate full amount of energy ⇒ rest dissipated as heat
- Effect of reverse bias estimated graphically by reflecting I-V curve of unshaded cells through the V = 0 axis
- Shaded solar cell is operating at intersection of its I-V curve and the reflected curve

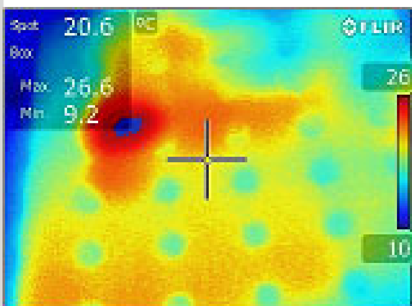


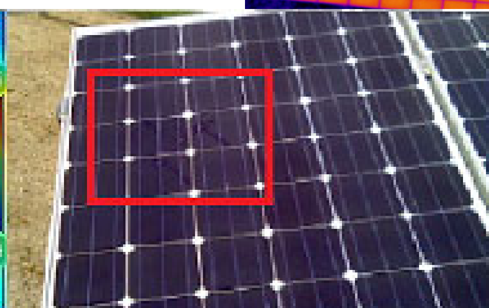
Source: textbook

Bypass Diodes







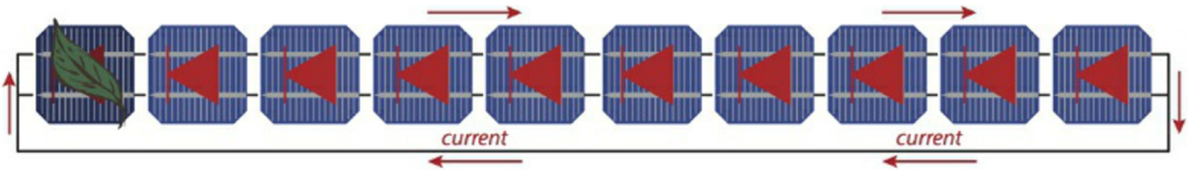


Source: https://www.pveducation.org/pvcdrom/modules-and-arrays/hot-spot-heating
https://pv-magazine-usa.com/2017/08/22/hot-spots-causes-and-effects/
https://www.ilumen.be/en/which-types-of-solar-panel-degradation-exist

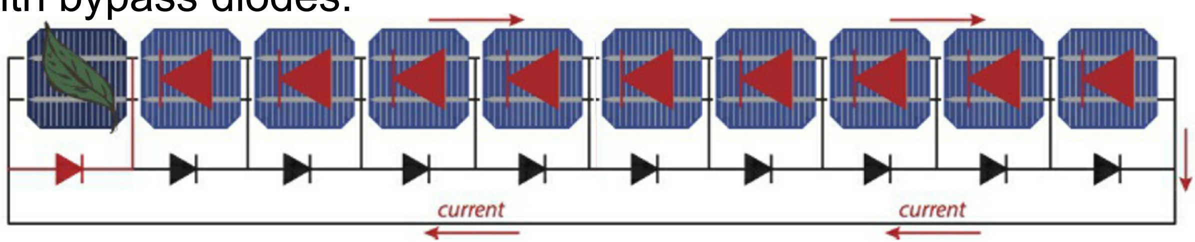
Bypass Diodes: Tutorial

- Step-by-step tutorial taken from PV Education considering the partial shading of 1 solar cell in a string of 10

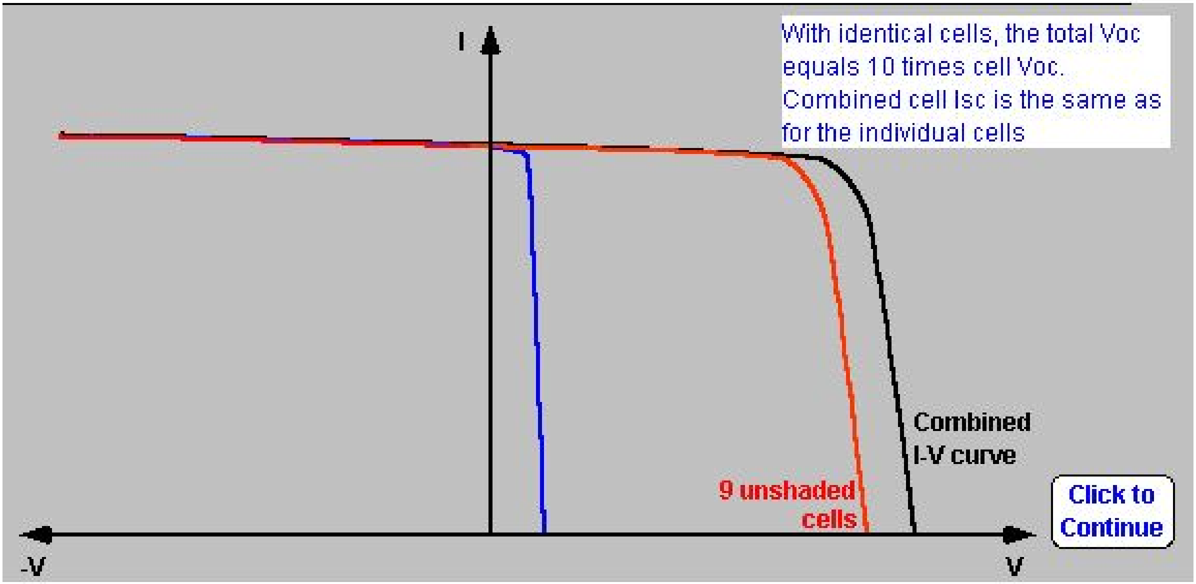
- Without bypass diodes:



- With bypass diodes:

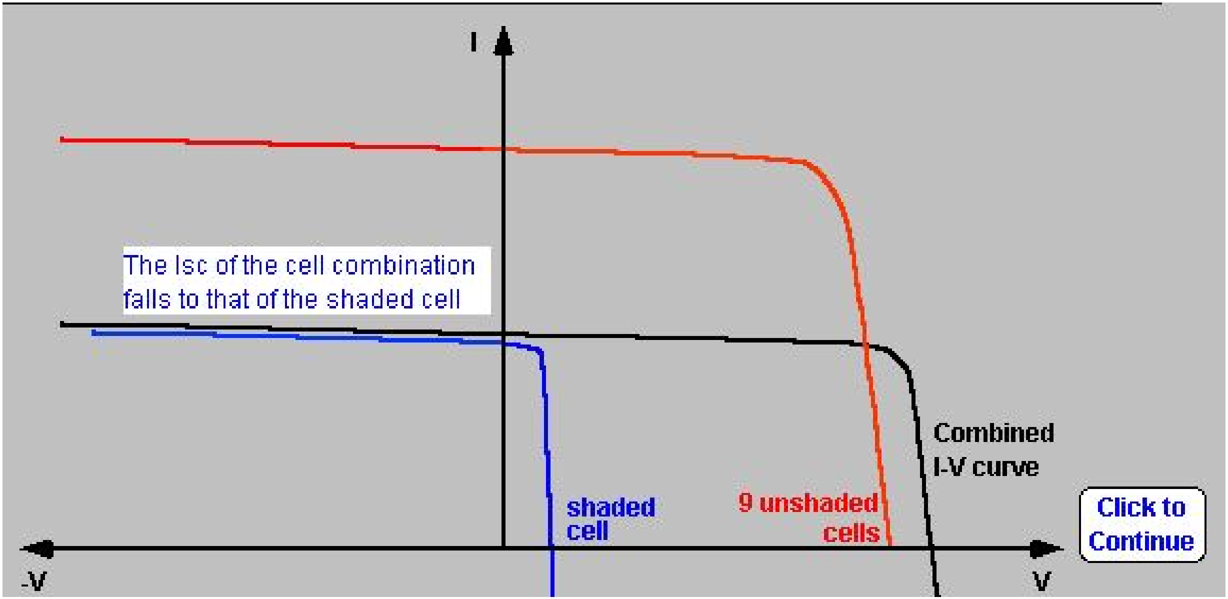


Bypass Diodes: Tutorial



Source: http://pveducation.org/pvcdrom/modules/bypass-diodes

Bypass Diodes: Tutorial



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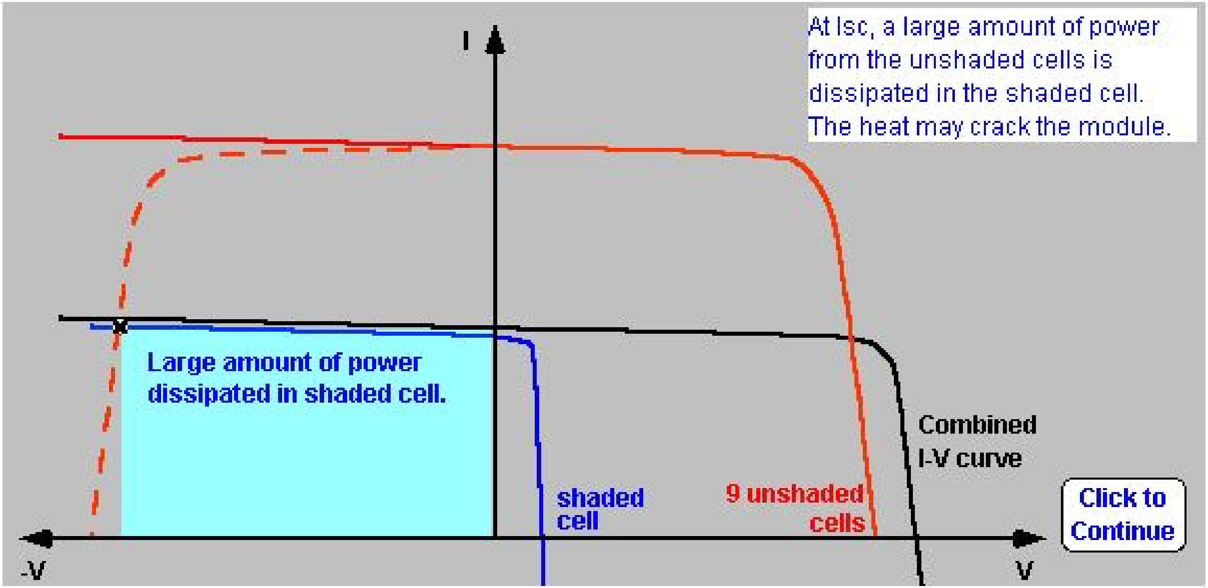
Bypass Diodes: Tutorial



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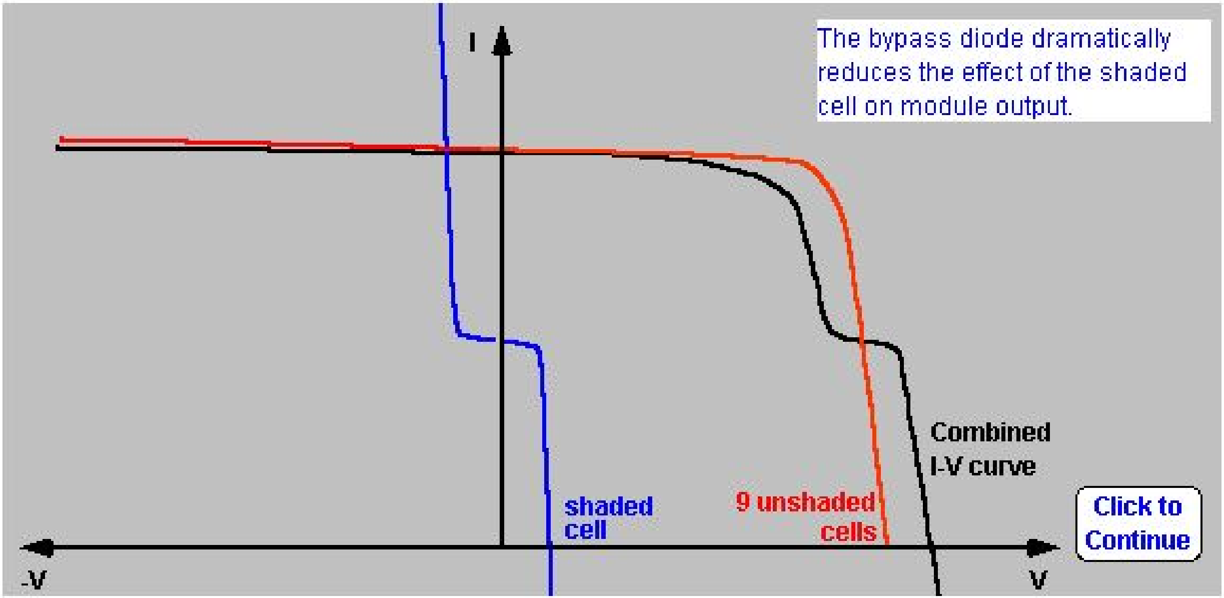
Bypass Diodes: Tutorial



Source: http://pveducation.org/pvcdrom/modules/bypass-diodes

Fabrication of PV Modules

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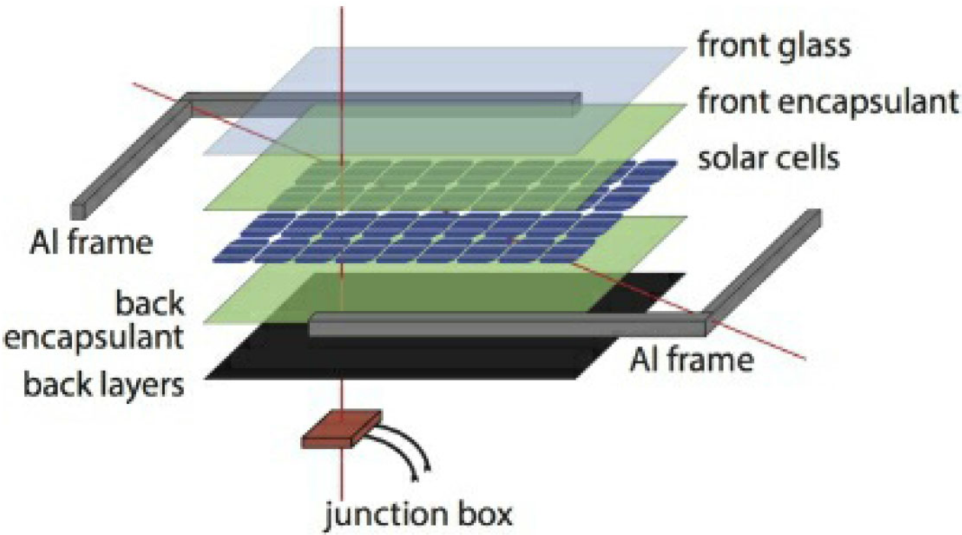
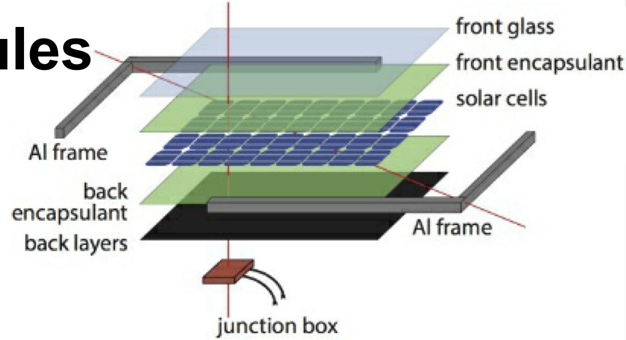
- PV module must have a lifetime of ≥ 25 years
- Module must be built of well-chosen and trusted components
- Components of a typical c-Si PV module:
  - Glass
  - Encapsulant
  - Solar cells
  - Back layers
  - Aluminium frame
  - Junction box



Source: textbook

Fabrication of PV Modules

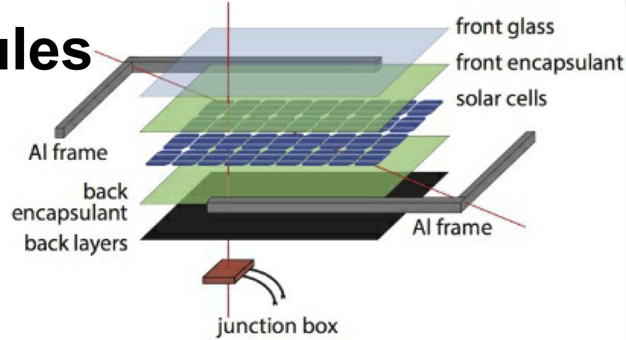


- Encapsulant:
  - Solar cells sandwiched in-between two layers of polymer encapsulant
  - Most common material is ethylene-vinyl-acetate (EVA), a thermoplastic polymer ⇒ best combination of properties (mechanical, thermal, optical, chemical) and price
  - Other encapsulants include:
    - polyvinyl butyral (PVB) – used in car windscreens
    - silicone – most transparent, but often too expensive

Source: textbook

Fabrication of PV Modules

- <u>Lamination</u>:
  - Most important step during PV module production – described below for EVA

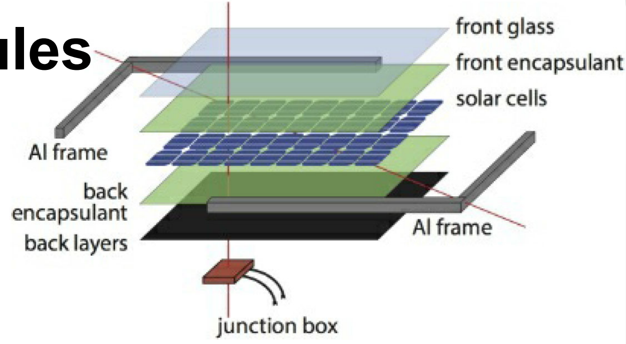


  - The whole stack (front glass, encapsulants, interconnected solar cells, back layer - just not frame and junction box) is placed in laminator

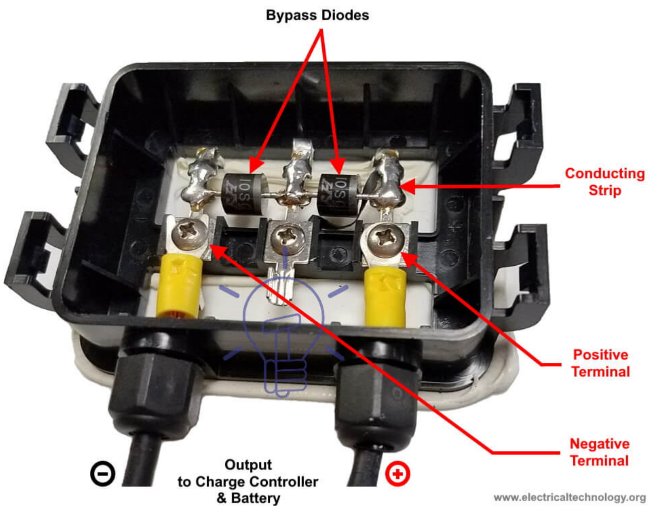
Source: textbook

Fabrication of PV Modules

- Frame (aluminium):
  put around whole module
  to enhance the mechanical
  stability



- Junction box (weatherproof):
  placed on rear of module –
  contains electrical connections
  to connect PV module to other
  components of PV system
  (also contains bypass diodes)



Sources: textbook
https://www.electricaltechnology.org/2019/10/blocking-bypass-diode-solar-panel-junction-box.html

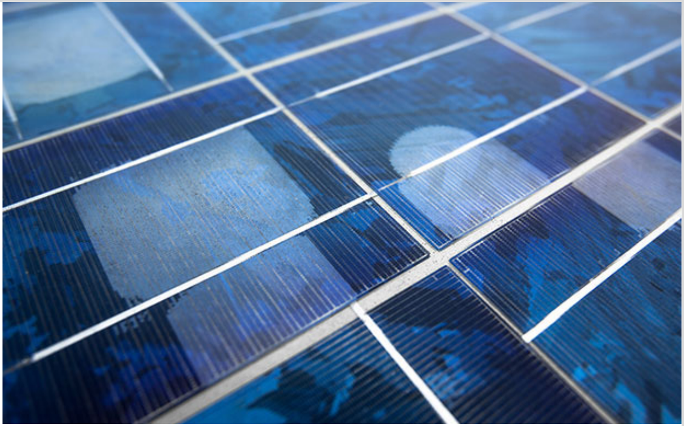
PV Module Lifetime Testing

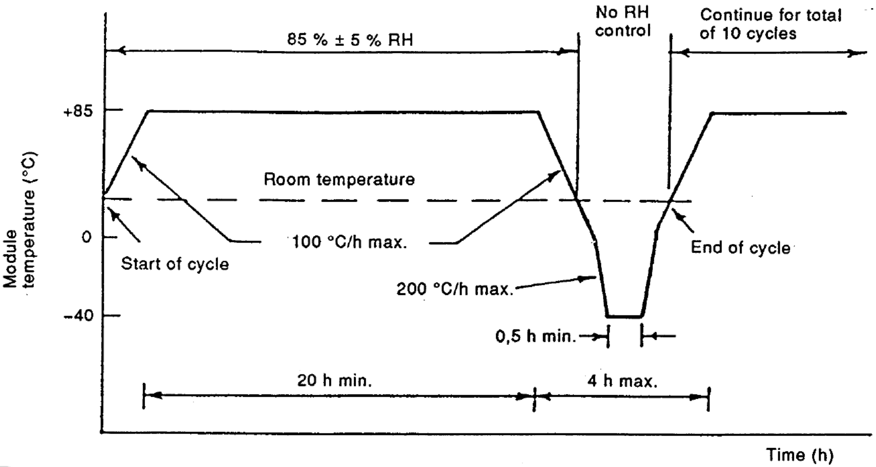
Karlsruher Institut für Technologie

- During 25 year lifetime, PV modules are exposed to wide range of external stresses:
- Temperature changes between night and day as well as between winter and summer;
- Mechanical stress for example from wind, snow and hail;
- Stress by agents transported via the atmosphere, e.g. dust, sand, and salty mist
- Humidity originating from the atmosphere;
- Moisture originating from rain, dew, frost, snow, ice
- Irradiance from the Sun, both direct and indirect $\Rightarrow$ high energy UV radiation is challenging for many materials, especially organic ones, e.g. EVA encapsulant contains UV absorbers

PV Module Lifetime Testing

2) <u>Humidity–freeze</u> tests for
   i) delamination of module;
   ii) adhesion of junction box





Temperature range similar to before, but now relative humidity also present (up to RH = 85%) $\Rightarrow$ 10 cycles

Source: IEC 61215 standard
https://review.solar/solar-panel-delamination/

PV Module Lifetime Testing

Karlsruher Institut für Technologie

Briefly:

5) Mechanical loads – test whether strong winds or heavy snow loads lead to structural failures, broken glass, broken interconnect ribbons or broken cells

6) Hot spot testing – check if hot spots are present – due to shunts in cells or inadequate bypass diode protection

7) Bypass diode – thermal testing to check if diode overheating could degrade encapsulant, back sheet or junction box

Source: https://www.youtube.com/watch?v=QMR_GpsrIzM

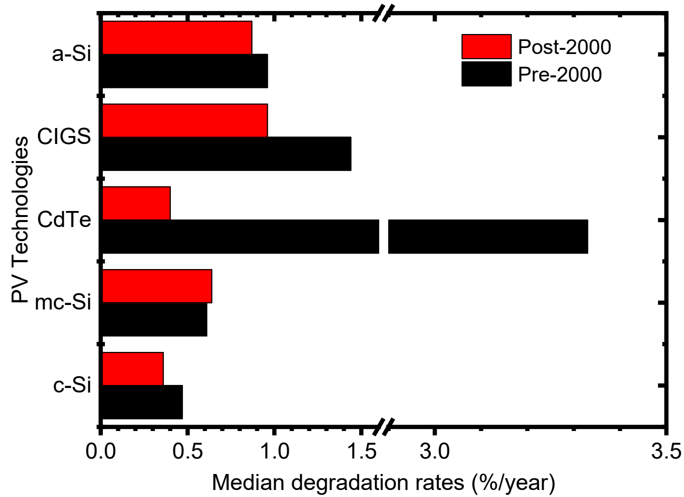
PV Module Lifetime Testing

- Meeting the IEC standard test is not a 25 year guarantee
- Actual lifetime not only determined by module design but also
  i) climate (e.g. hot-dry or warm high-humidity) and
  ii) final application (e.g. roof-integrated or free-standing)
- Other relevant standards:
  - IEC 61646 – very similar to IEC61215 but for thin-film PV modules and includes a "light soaking" step (5.5 kWh/m^2)
  - IEC 61730 – Hazards from handling module (Electrical, mechanical, thermal) and fire resistance
  - IEC 61701 – salt corrosion testing, e.g. lighthouse PV panels
  - Qualification tests carried out by independent organizations
    ⇒ TÜV Rheinland in Germany.

Source: IEC 61215 standard

PV Module Lifetime

- PV module performance degradation rates are typically 0.5% (relative) p.a. for c-Si and CdTe
- mc-Si, CIGS and a-Si exhibit slightly worse degradation over time
- Degradation rates of all PV modules improving with time
- A third party “reinsurance company” ensures these warranties are valid in case manufacturer goes bankrupt



Source: Li, Cai, Schäfer, Richards, Applied Energy, 253 (2019): 113524

PV Modules

- Indeed, there are c-Si PV modules that are >40 years old and still working, e.g.:
- 1959 Hoffman solar radio (also built first solar-powered space satellite)
- 1980 Arco Solar c-Si PV panel – initial rating 33W – similar when tested again outdoors in 2010 (not under STC)

Source: https://en.wikipedia.org/wiki/Les_Hoffman
https://www.greenbuildingadvisor.com/article/testing-a-thirty-year-old-photovoltaic-module

Thin-Film PV Modules

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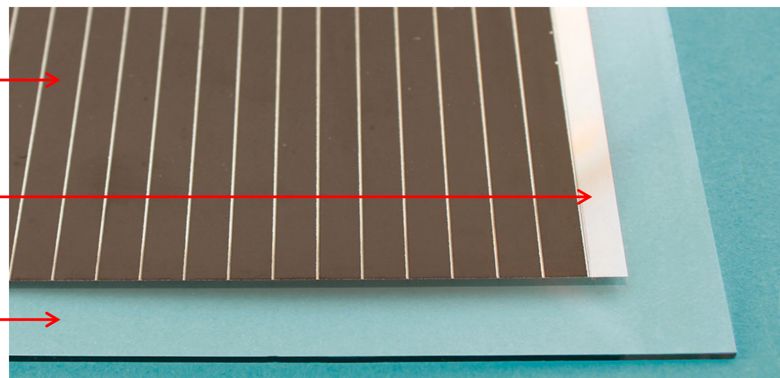
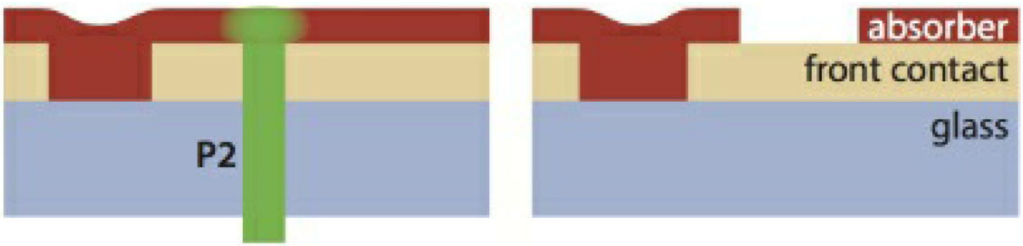
- Thin-film PV module ⇒ consists of strips of many narrow cells of ~0.5 – 1 cm width and length being equal to module length
- Cells are connected in series across the width of module
- Metallic busbars on left and right of module collect the current and conduct it to bottom to connect to external cables
- Busbar shown here for CIGS module



Source: https://www.4micro.de/en/solutions/bus-bar-exposure/

Thin-Film PV Modules

- Second laser scribe (**P2**) is performed – now using a laser wavelength such that it is primarily absorbed by absorber layer and not TCO
- E.g. for a-Si:H solar cell a $\lambda = 532$nm green laser often used

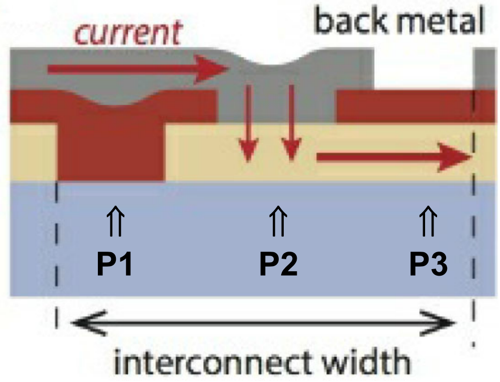


- **P2** scribe leaves a gap in the absorber layer

Source: textbook

Thin-Film PV Modules

- Understanding scribes **P1, P2, P3**
- **P1** scribe filled with absorber material ⇒ forms <u>barrier</u> since absorber is orders of magnitudes less conductive than TCO
- Similarly, **P3** scribe forms <u>insulating gap</u> in metallic back contact
- However, **P2** scribe that is filled with metal forms a <u>highly conducting connection</u> between the front and back contacts ⇒ achieves series connection



Source: textbook

CIGS Thin Film PV Modules

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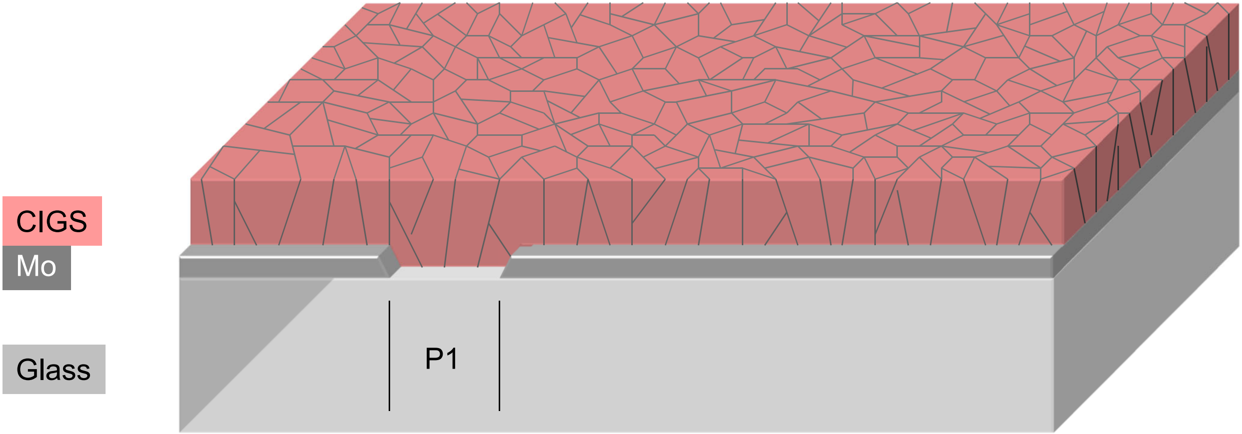
Step 2: DC sputtering of molybdenum back contact

Source: Powalla, ZSW

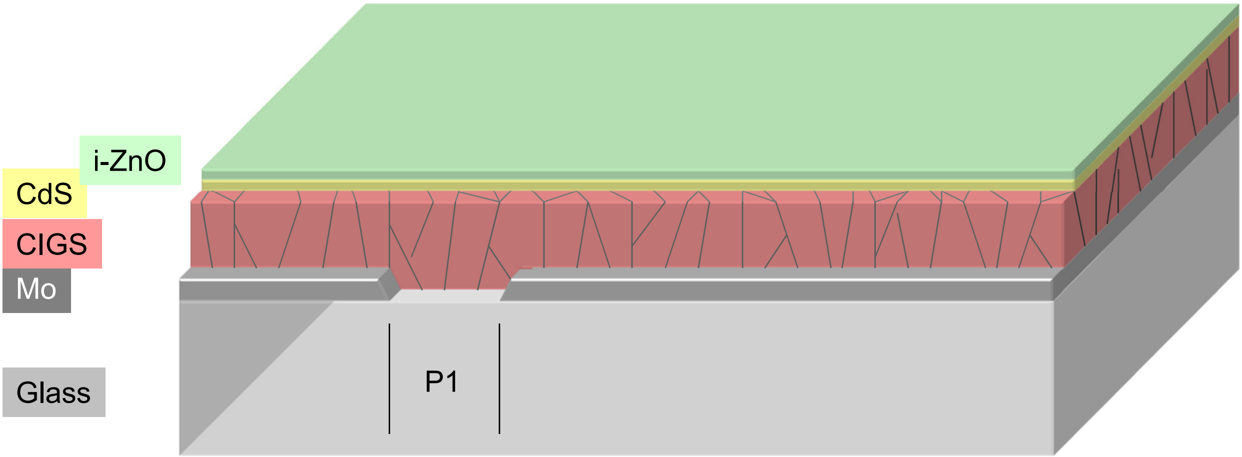
CIGS Thin Film PV Modules



Step 4: Evaporation of $Cu(In,Ga)Se_2$

Source: Powalla, ZSW

CIGS Thin Film PV Modules



Step 6: RF sputtering of i-ZnO

Source: Powalla, ZSW

CIGS Thin Film PV Modules

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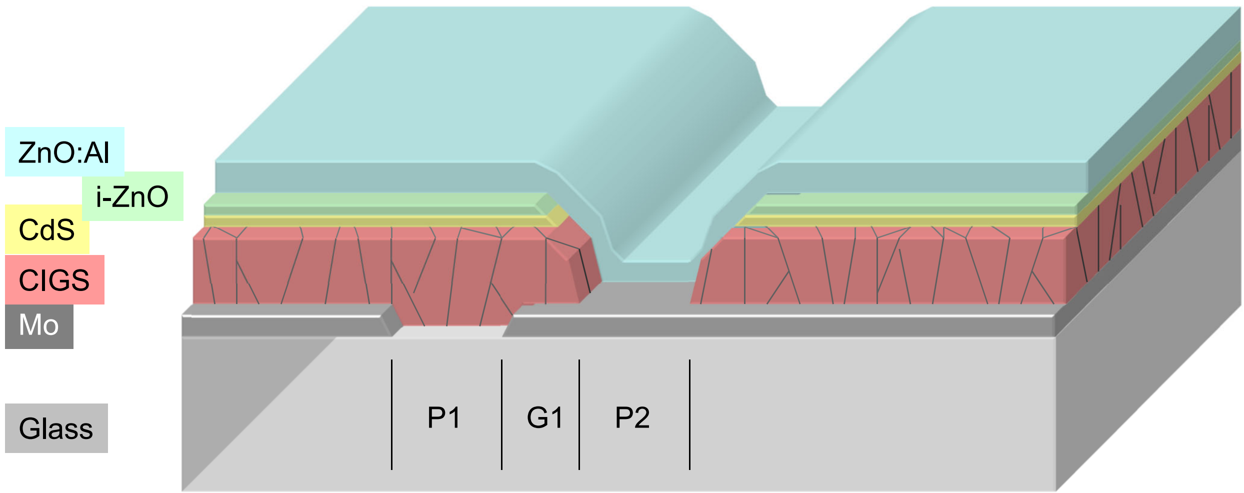
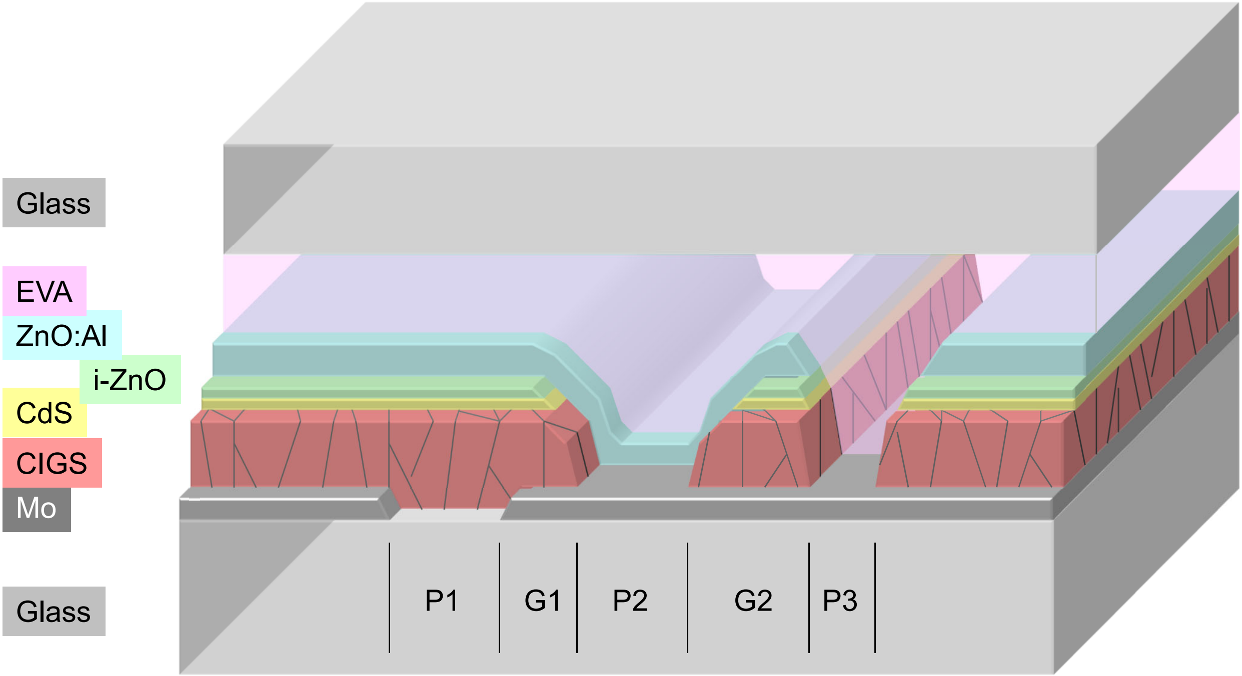


Step 8: Sputtering of ZnO:Al (TCO)

Source: Powalla, ZSW

CIGS Thin Film PV Modules



Step 10: Encapsulation with polymer foil and glass

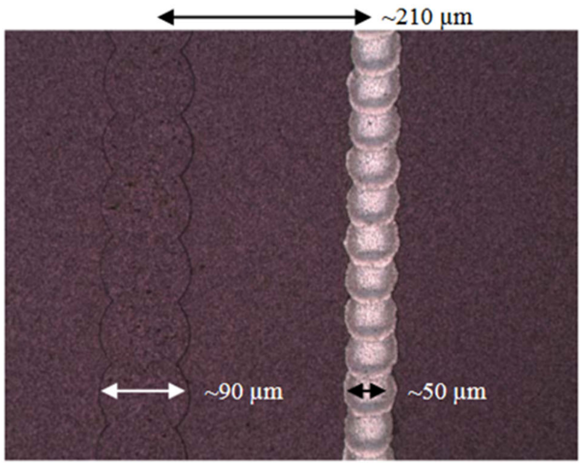
Source: Powalla, ZSW

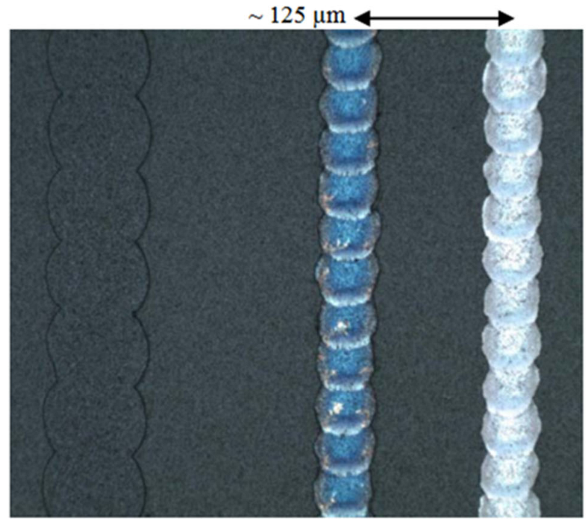
Thin-Film PV Modules

- Requirements of laser for good interconnect performance
- P2 scribe has to be highly conductive ⇒ wide enough plus no barrier at interface between the TCO and metal
- P1 and P3 scribes must form good barriers to effectively separate cells from each other
- Region between P1 and P3 scribes does not contribute to the photocurrent generated by the module ⇒ "dead area" ⇒ Thus ratio between this width and the total cell width (including the scribes) should be as small as possible
- Also, three laser scribes are performed in different steps of production and thus with different machines ⇒ alignment in all the production steps is extremely important for manufacturing high quality thin-film PV modules

CIGS PV modules

- For CIGS R&D devices, dead region ~400μm wide
- Total cell typically 3 – 5mm wide ⇒ thus dead region ~10%
- Similar to ~8% shading from front contacts in c-Si solar cells

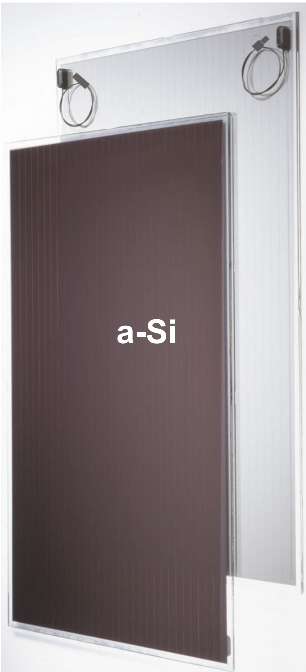


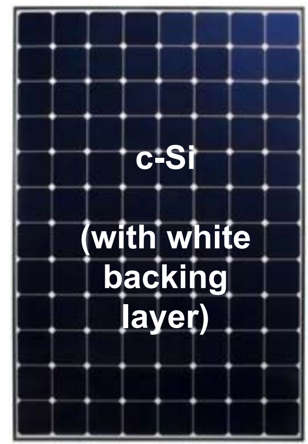


P1 **P2** **P1** **P2** **P3**

Source: https://www.nrel.gov/docs/fy11osti/49411.pdf

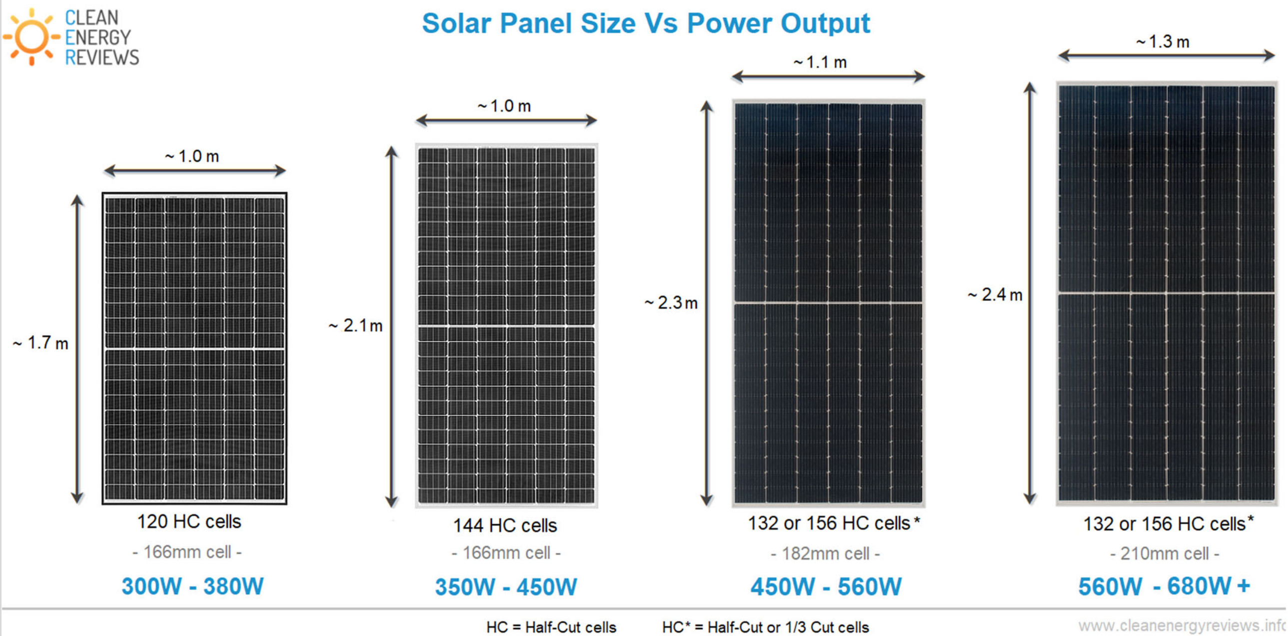
Examples of PV Modules





Photos: CIGS (Manz), a-Si (Schott Solar), CdTe (First Solar), c-Si (Sunpower Corp.)

Examples of PV Modules



- Both cell number and module size keeps growing!

Source: https://www.cleanenergyreviews.info/blog/most-efficient-solar-panels