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FABRICATION OF AL-BSF CELLS AND CRYSTALLINE-SILICON-BASED MODULES

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This lecture will be recorded.

CONTENTS

1. Intro: main design considerations
2. Al-BSF cell parts
3. Al-BSF cell production
4. c-Si module production

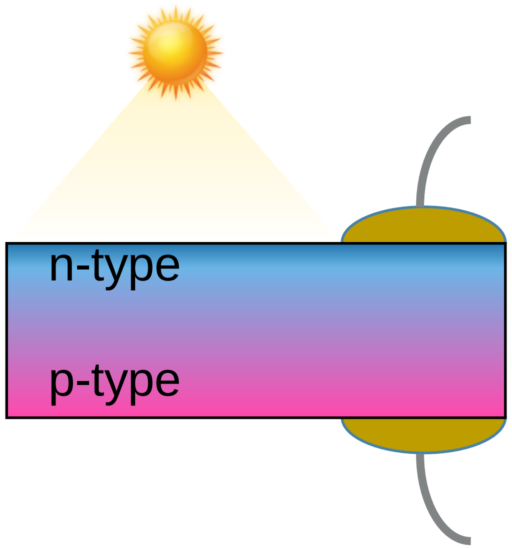
Recommended reading:

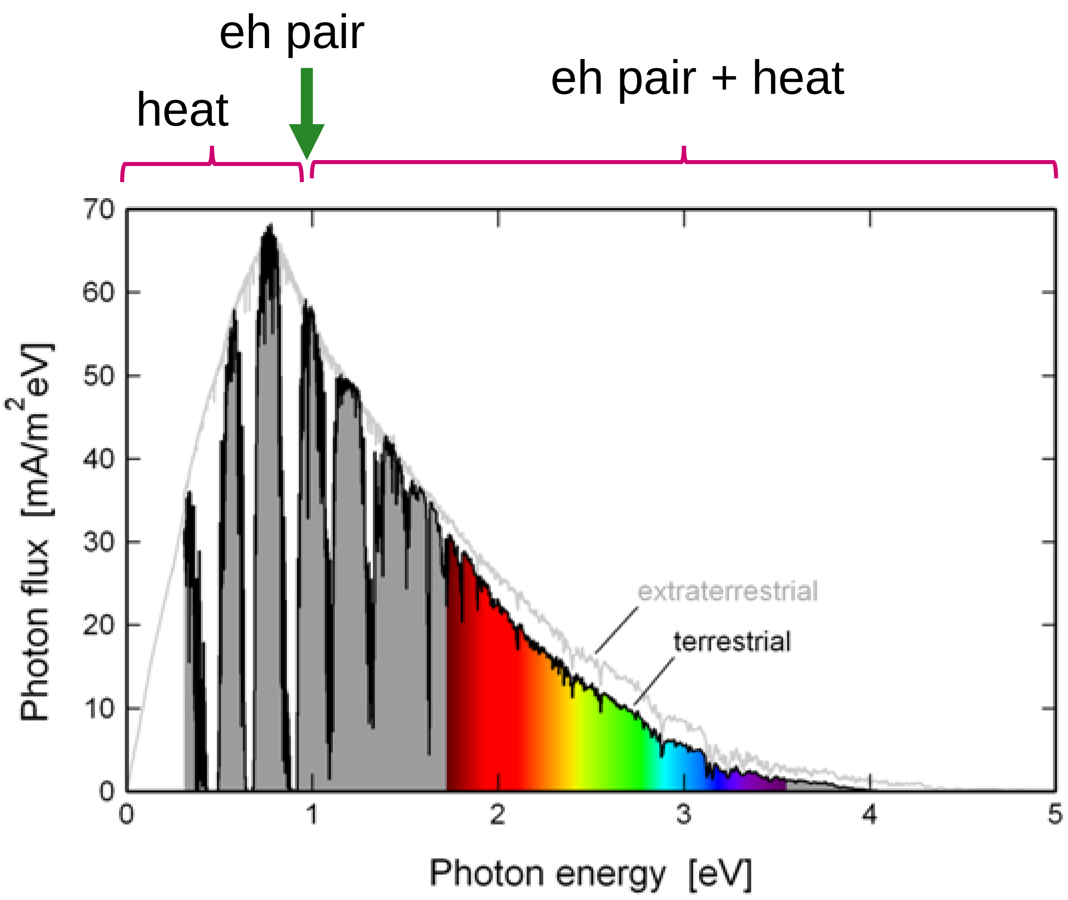
- Archer and Hill
- pveducation.org
- …

1. MAIN CELL DESIGN CONSIDERATIONS

WHAT LIMITS THE EFFICIENCY
(IN A PN JUNCTION SOLAR CELL)

- The broad spectrum of sunlight
- Electron-hole recombination
- Series resistance
- Reflection
- Self-heating





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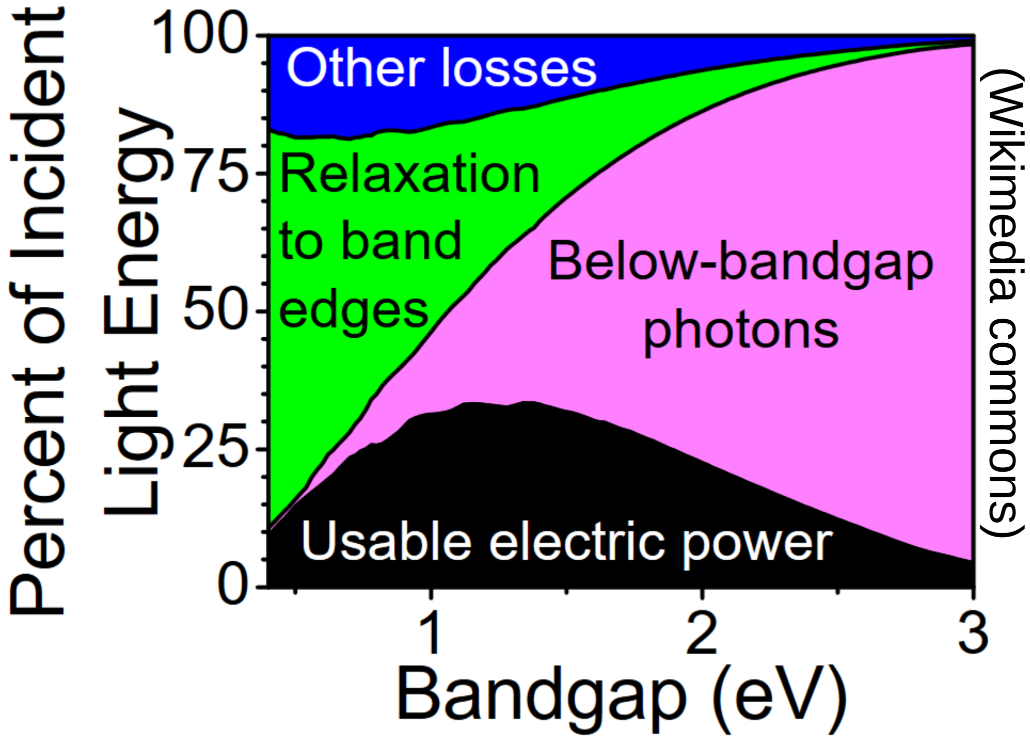
THE SHOCKLEY-QUEISSER LIMIT
W. SHOCKLEY AND H.J. QUEISSER, 1961

The SQL for silicon:

- A silicon p-n junction cell has a maximum η = 30%.
- Later, refined calculation:
  - p-n junction cell max η = 33.7% with bandgap of 1.34 eV
  - For silicon, max η = 32%
- Now, 61 years later, we are at 26.1% in the lab, and >20% on the roof.
  (single-crystal Si, non-concentrator)

The SQL for all bandgaps:



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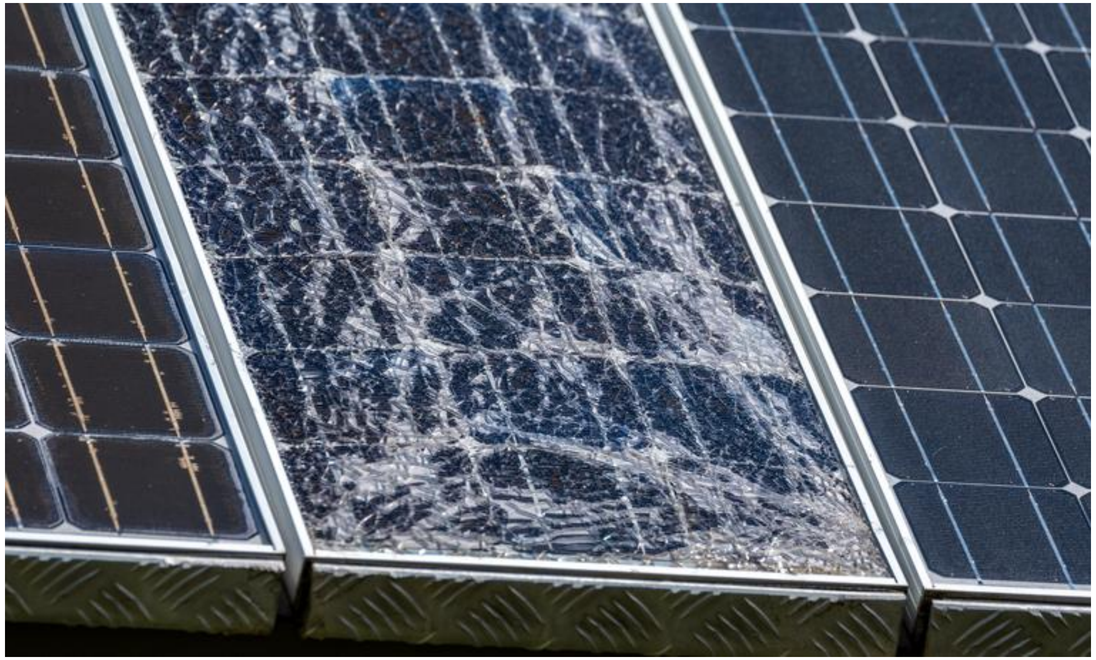
NOT ONLY EFFICIENCY MATTERS!

A good solar cell:

- Is cheap to produce
- Uses no scarce materials
- Produces much more energy than it took to make it
- Requires no maintenance
- Works for more than 20 years



These criteria are met with the Al-BSF cell.

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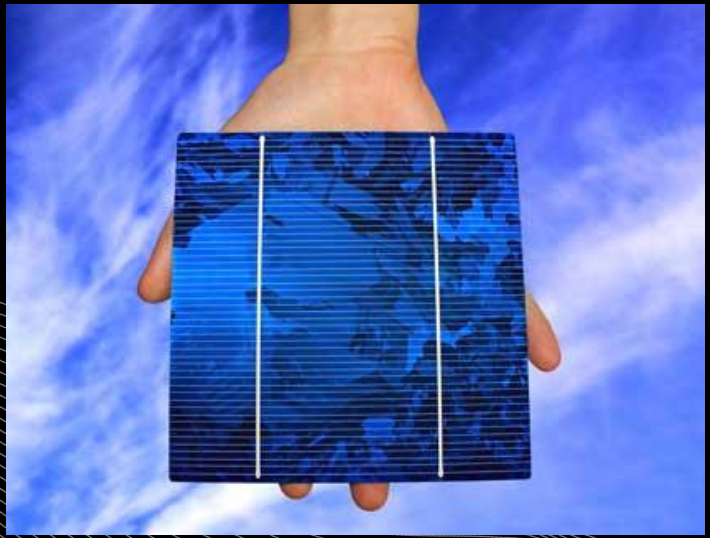

2. AL-BSF: THE MOST COMMON SOLAR CELL

THE MOST COMMON SILICON SOLAR CELL

The insider's name is:
Al-BSF on p-type silicon
Efficiency: 15-21%

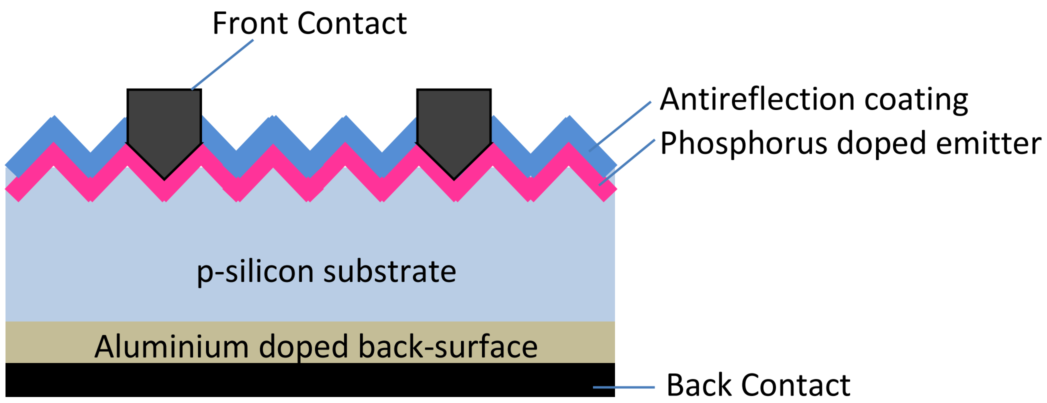

Figure 3.2.4 Screen-printed silicon solar cell

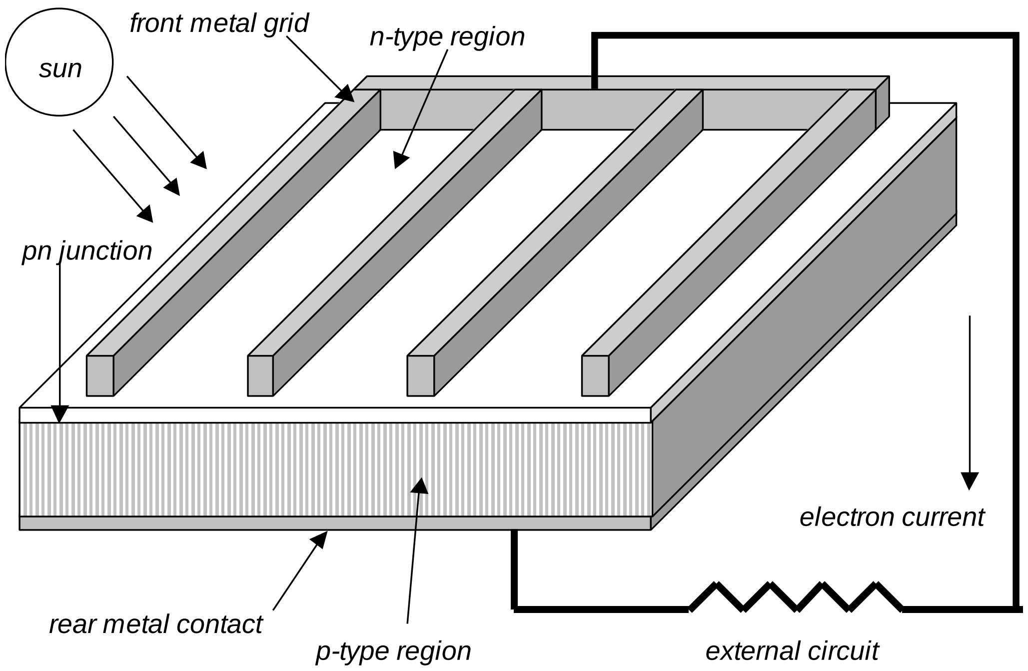

Figure 3.2.1 Schematic of a typical solar cell

Note: these images are not to scale.
The wafer is 150-200 µm, the top and bottom layers only a few µm.

Figures from: Reinders, Verlinden, Van Sark and Freundlich: Photovoltaic Solar Energy

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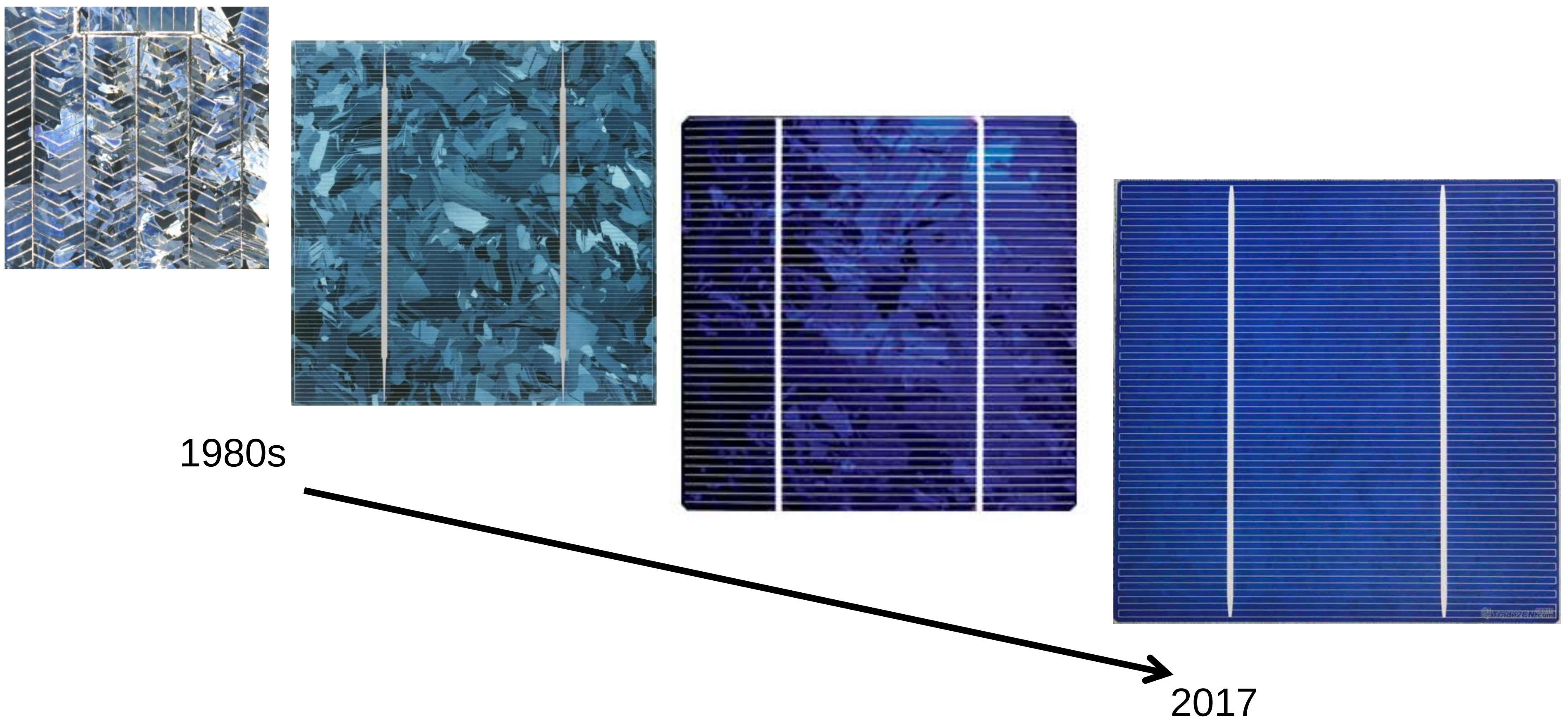
MULTICRYSTALLINE SILICON SOLAR CELLS



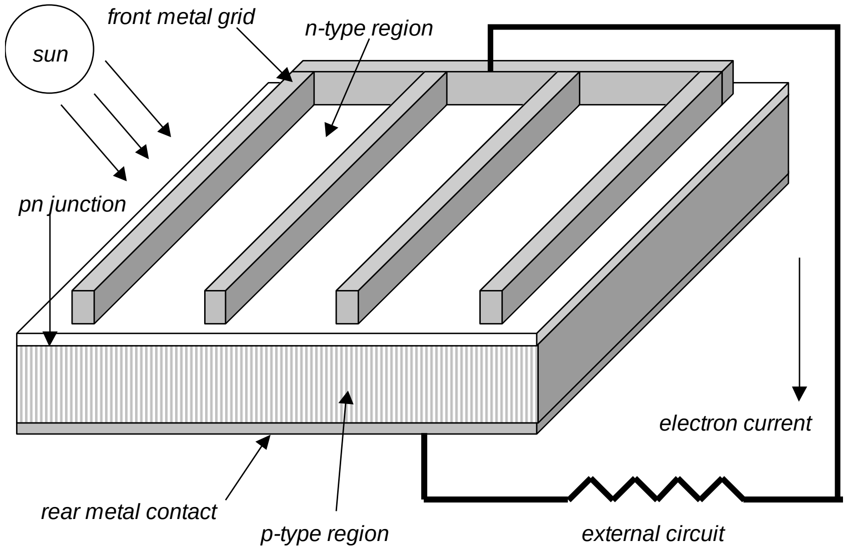
1. FRONT METAL GRID

Needed to get the electrons out

- More metal: more reflection
- Less metal: more resistance

→ Use the best conductor: Ag

- Large contributor to cell cost
- We lose 2-5% of the light by reflection off the top metal



Material	Conductivity σ (MS/m) at 20°C	Market price €/kg (2 March 2020)
Silver	63	490
Copper	60	5.1
Gold	45	46,700
Aluminum	35	1.5
Zinc	17	1.8
Iron	10	0.1
Platinum	9	25,200

Table: the best-conducting metals.

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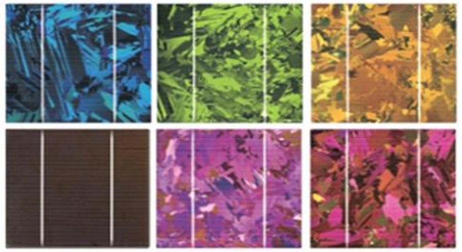
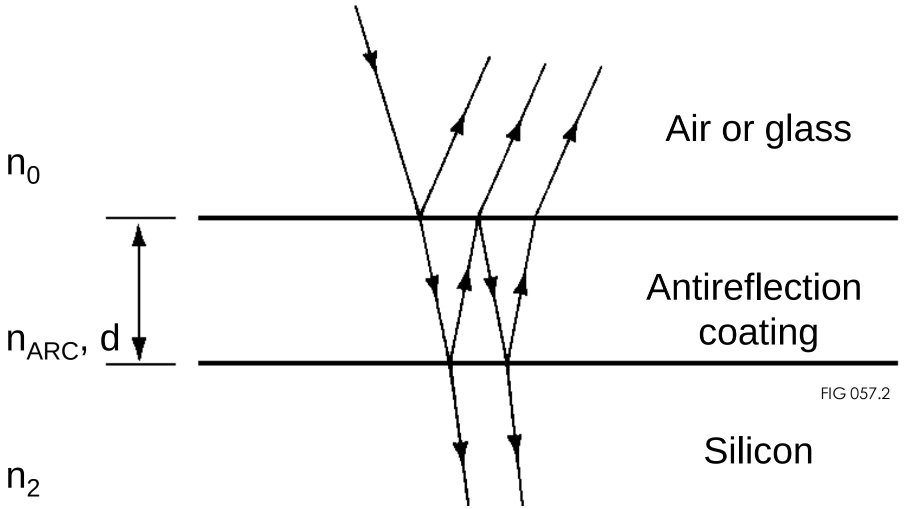
2. ANTI-REFLECTIVE COATING

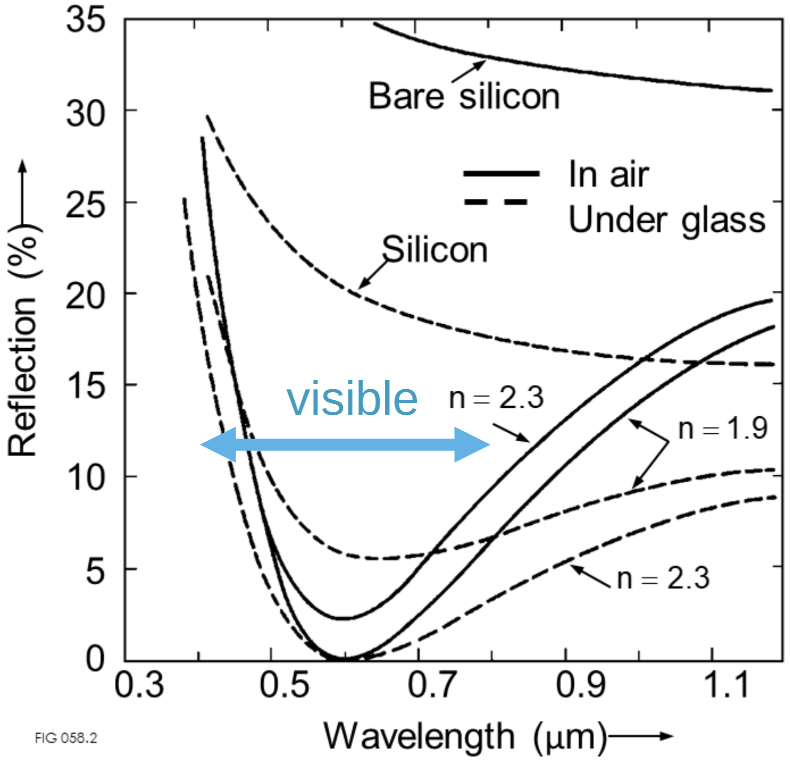


- Bare silicon has a high surface reflection of over 30%.
- An ARC reduces reflection by interference.

$$n_{ARC}d = \frac{\lambda_0}{4}$$

$$n_{ARC} = \sqrt{n_0 n_2}$$





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3. TEXTURING

- “Roughening” of the surface
- Enhances the absorption

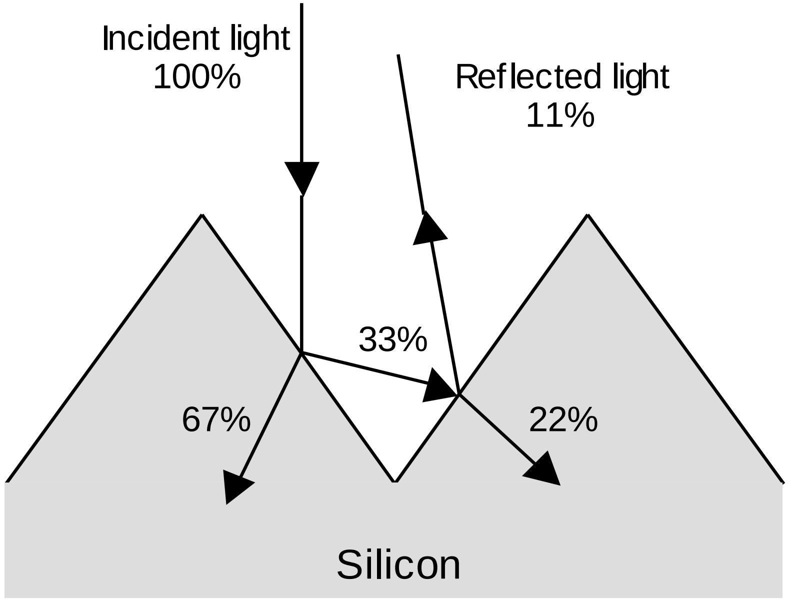
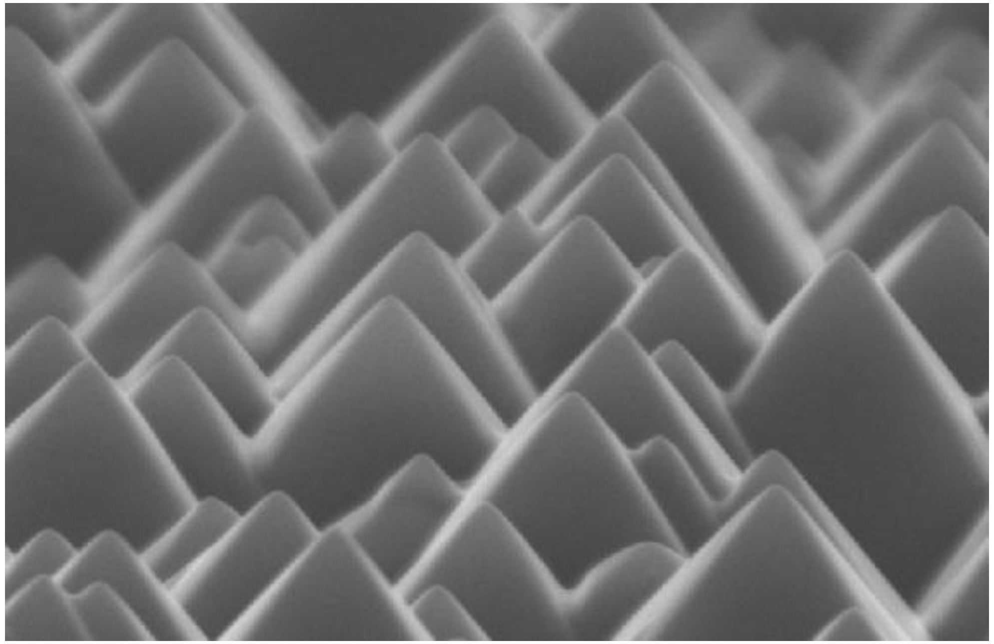


Figure from: Reinders, Verlinden, Van Sark and Freundlich: Photovoltaic Solar Energy



Scanning electron microscope photograph of a textured silicon surface. Image courtesy UNSW.

4. THE ABSORBER: SILICON

- ARC + texturing: only a few % reflection remains
- Does silicon absorb the rest?
  - Not the photons with $E < E_g$
  - The rest: 75% in the first 20 µm
  - Wafer is 150 – 200 µm thick
  - Infrared is difficult

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4. THE ABSORBER: SILICON

- ARC + texturing: only a few % reflection remains
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  - Not the photons with $E < E_g$
  - The rest: 75% in the first 20 μm
  - Wafer is 150 – 200 μm thick
  - Infrared is difficult (next slide)

p-n junction:

- We buy p-type Si (cheapest)
- These are boron-doped
- We over-dope one side n-type
- Phosphorus easiest

Don’t get confused:

- P = phosphorus, n-type dope
- p = positive, boron dope

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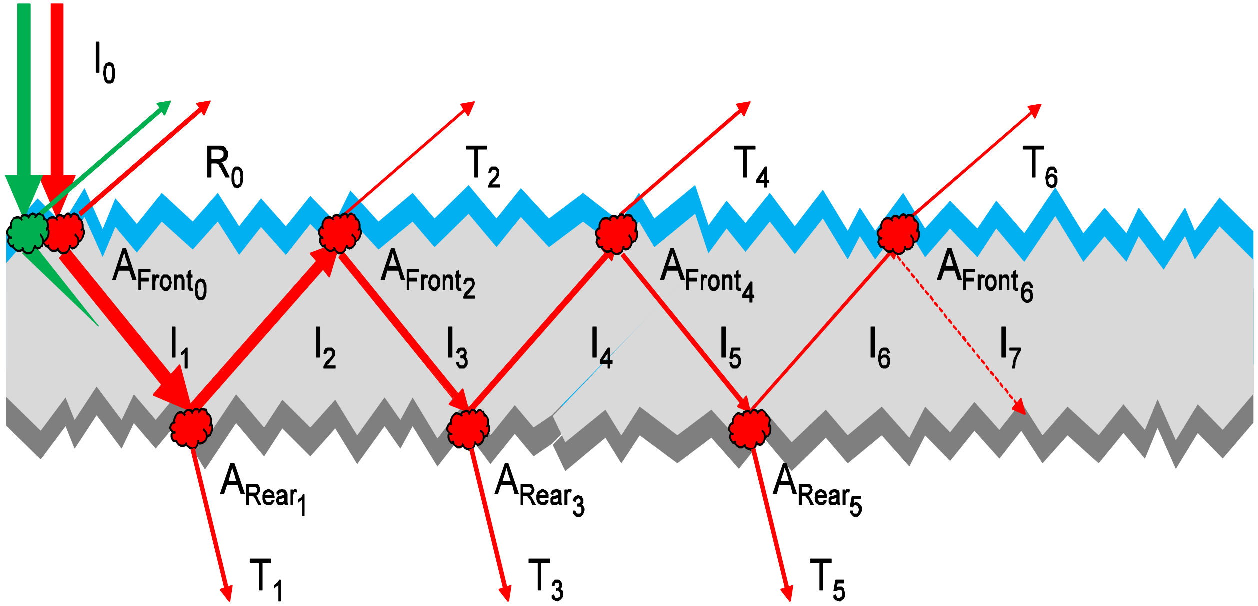
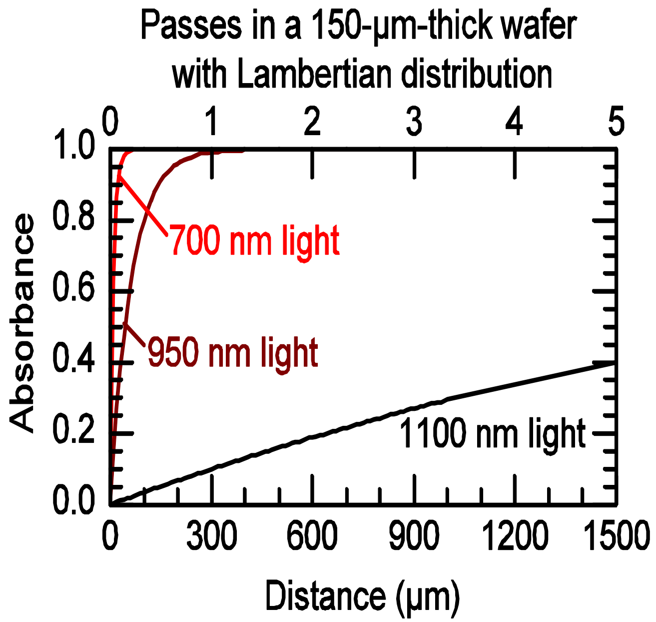
ABSORBING INFRARED VERSUS VISIBLE





Texturing helps to keep the infrared light inside the silicon wafer and increase its absorption

Figures from: Reinders, Verlinden, Van Sark and Freundlich: Photovoltaic Solar Energy

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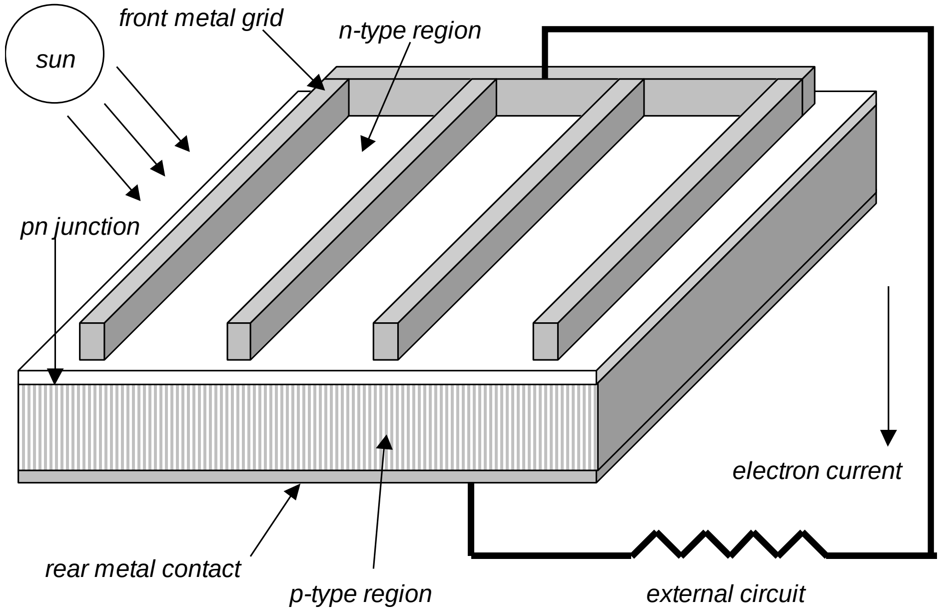
5. THE REAR METAL CONTACT

- A continuous layer is cheaper to make than lines, but uses more metal
- A continuous layer conducts better
- Contrary to the front side, we *want* to reflect light, here
- Aluminum is much cheaper than Ag

- But: metal on silicon gives a lot of e-h recombination… we don't want that.



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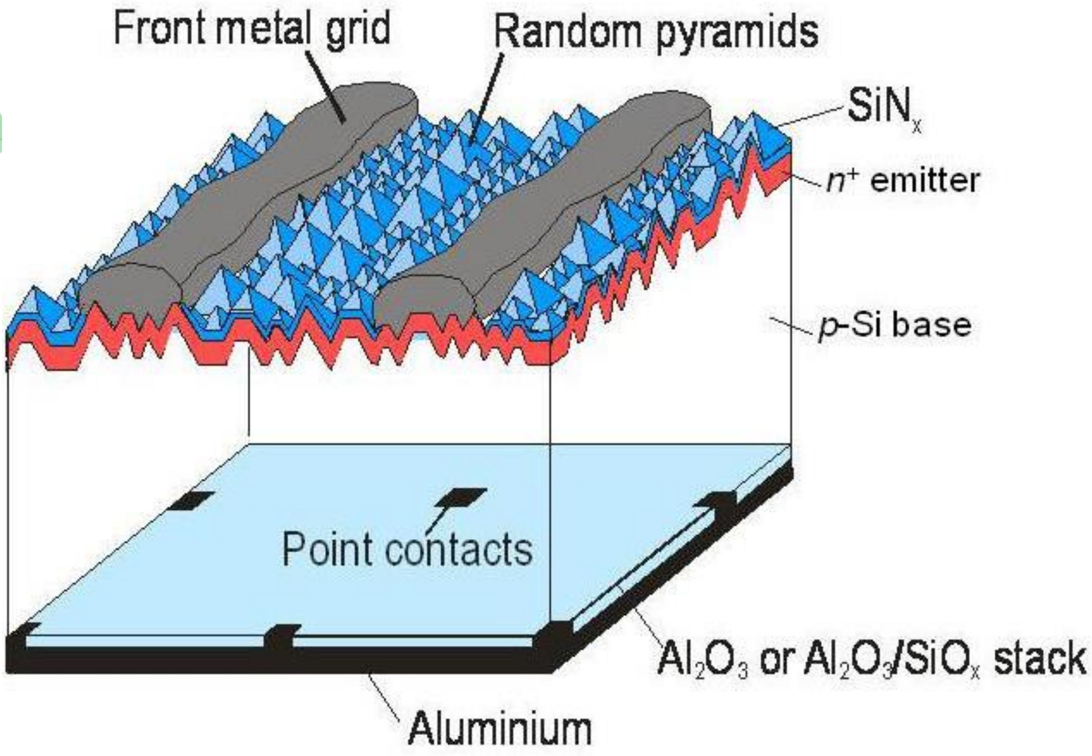
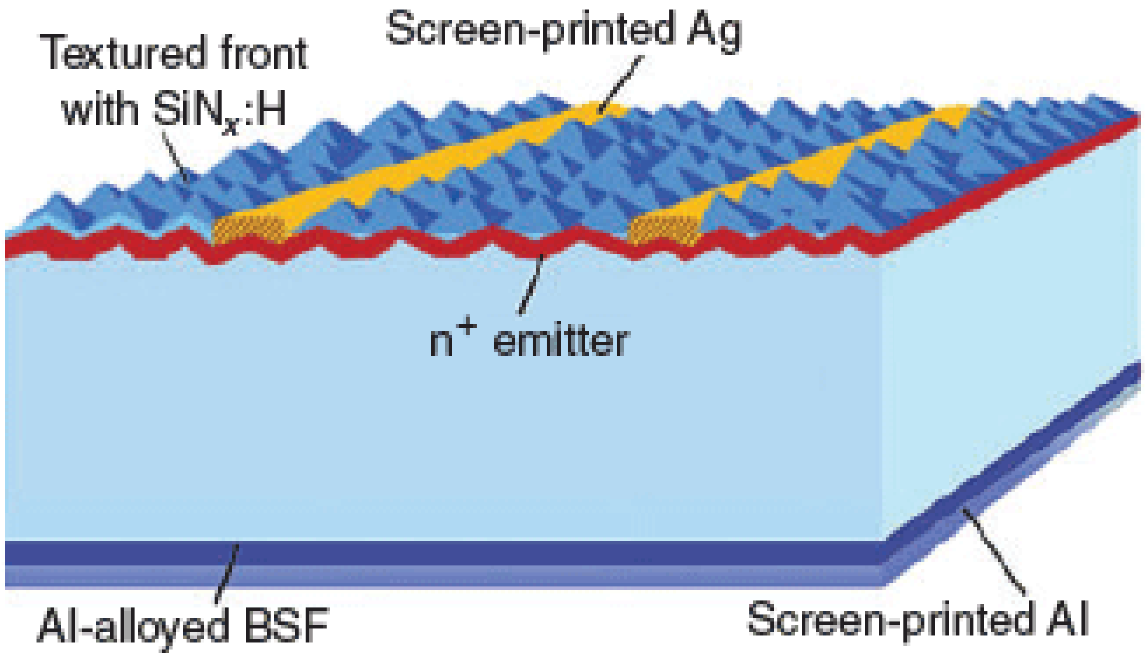
RECOMBINATION AT THE REAR CONTACT: TWO STRAIGHTFORWARD SOLUTIONS

- Only make sparse contacts



- Suppress surface recombination by “BSF”



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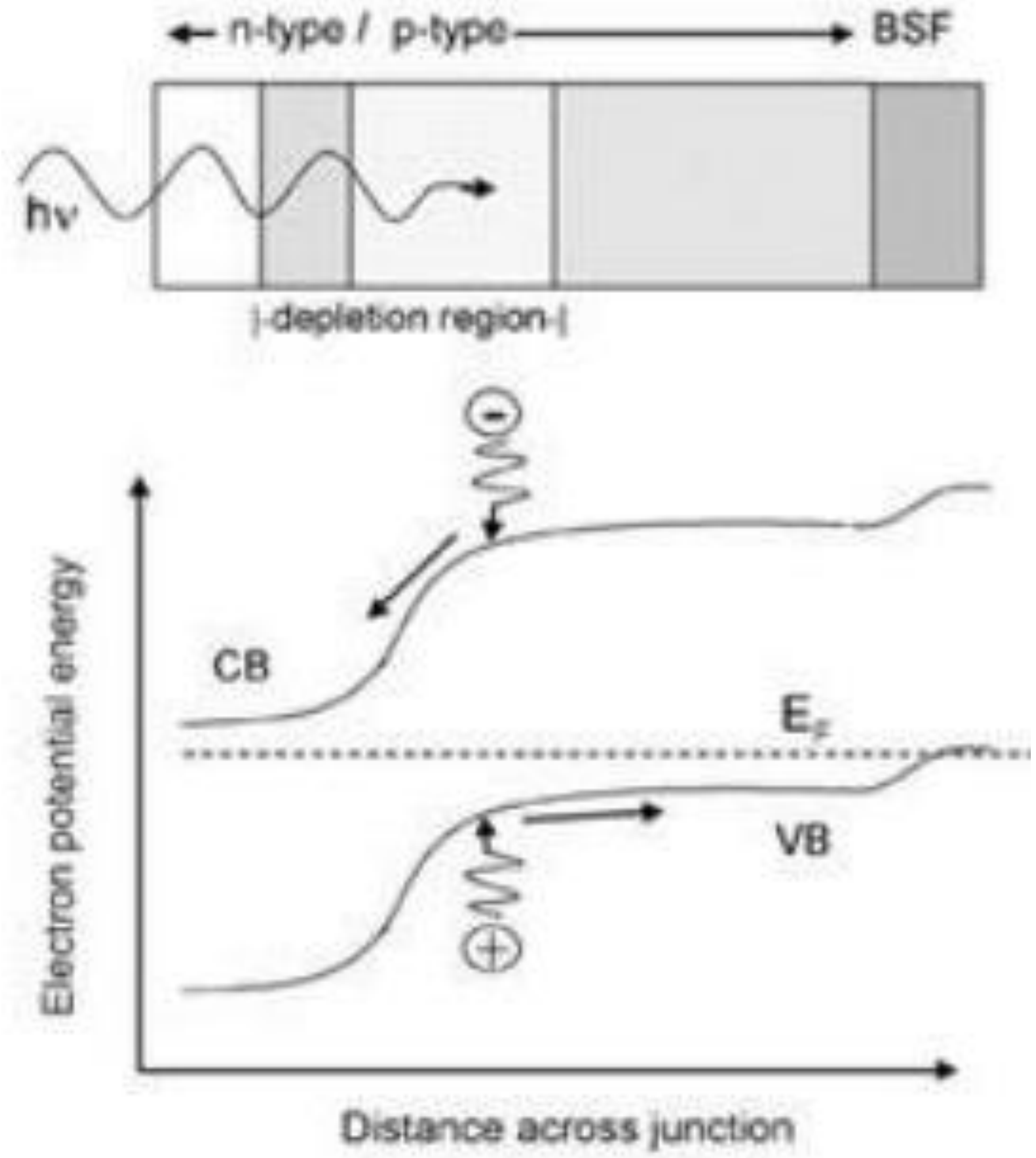
AL-BSF

- “Back Surface Field”
- Youtube Video explains this
- We want to collect the holes
- Create a p+ region:
    - This means, high p-type doping
    - Can be done with B or Al
- Now, electrons are pushed away from the contact
- Then, no recombination at the metal-silicon junction



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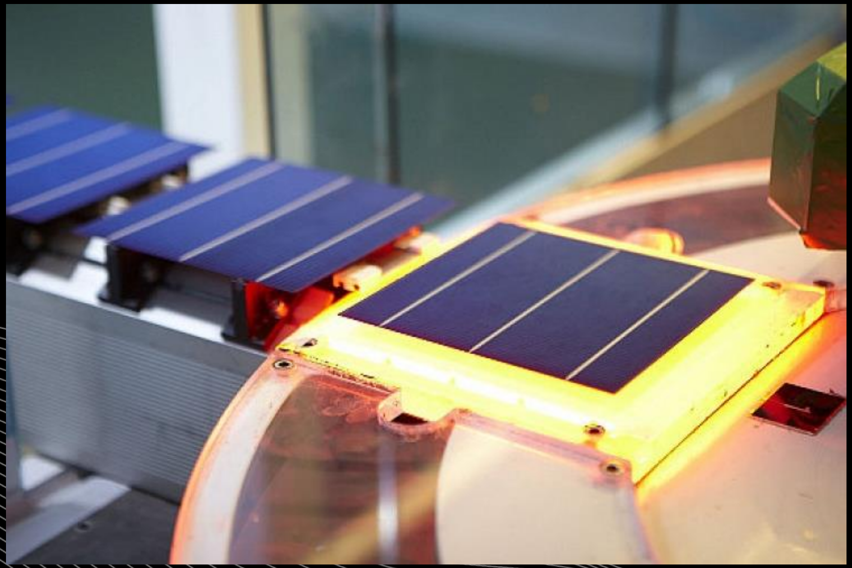


3. MAKING AL-BSF SOLAR CELLS

HOW IT'S MADE

- 6 process steps to make a solar cell from a silicon wafer.
- Cost and production speed are crucial
- The wafer used to be the most expensive part
- Now, it's the Ag lines on top

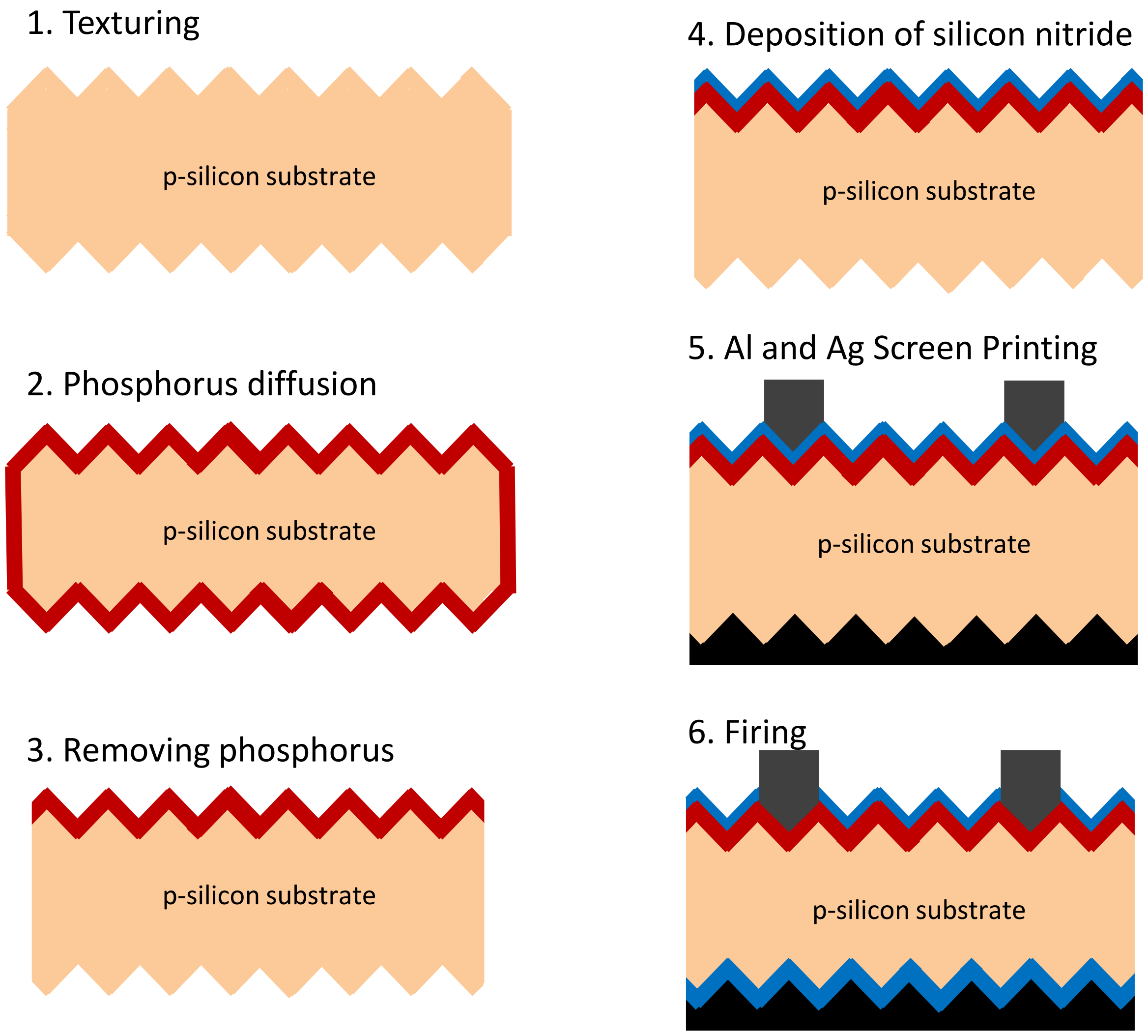
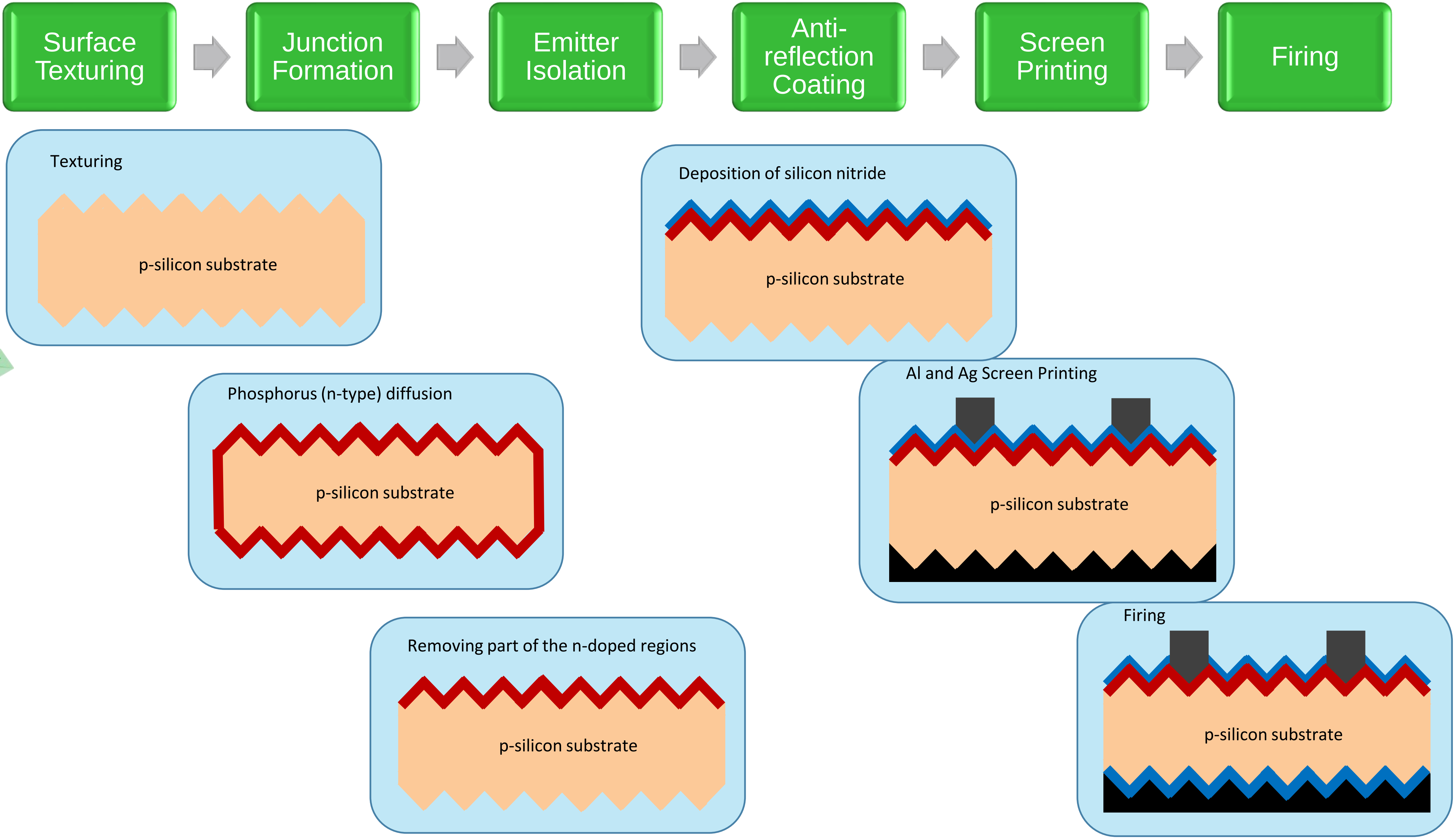


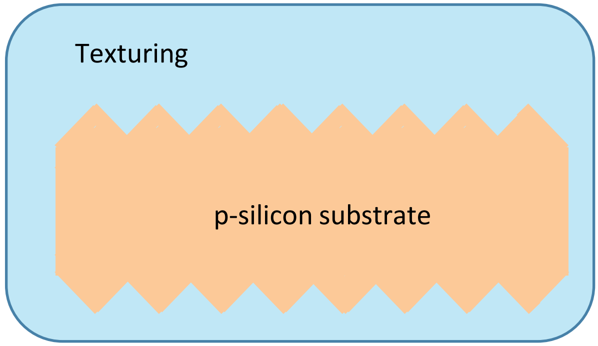
Figure 3.2.3 A typical process of a screen-printed silicon solar cell.


Surface Texturing
Junction Formation
Emitter Isolation
Anti-reflection Coating
Screen Printing
Firing
Texturing
p-silicon substrate
Phosphorus (n-type) diffusion
p-silicon substrate
Removing part of the n-doped regions
p-silicon substrate
Deposition of silicon nitride
p-silicon substrate
Al and Ag Screen Printing
p-silicon substrate
Firing
p-silicon substrate

Surface Texturing → Junction Formation → Emitter Isolation → Anti-reflection Coating → Screen Printing → Firing

- **Surface texturing** to reduce reflection losses of solar cells
- Monocrystalline wafers:
  chemical bath with alkaline solutions (NaOH / KOH / TMAH*)
  reflection loss reduced to 11%
- Multi-crystalline wafers:
  chemical with acidic solutions, f.i. HNO_3 and HF
  reflection loss reduced to 23-25%

*Tetramethylammonium hydroxide



Surface Texturing → **Junction Formation** → Emitter Isolation → Anti-reflection Coating → Screen Printing → Firing

- Create an n-type layer (“emitter”) in a p-type (“base”) silicon wafer
- Step 1: $POCl_3$ (g) + O_2 (g)$\rightarrow$ P_2O_5 (s), in a furnace at 800-900 °C.
  Step 2: $2P_2O_5 + 5Si \rightarrow 5SiO_2 + 4P$
  The elemental phosphorous, P diffuses into the wafer.
- Cheaper alternative: spraycoating of liquid H_3PO_4 on top of the wafer, followed by heating in a furnace; the P diffuses into the wafer.

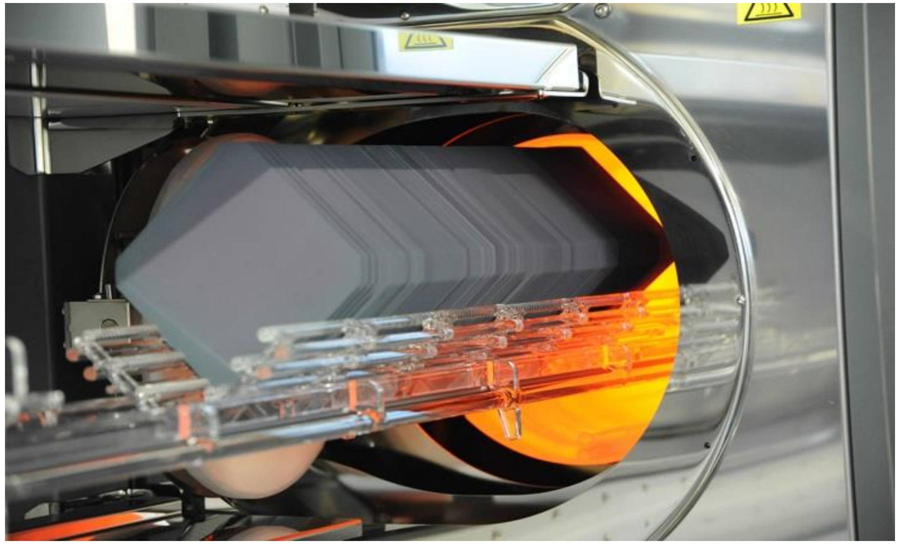
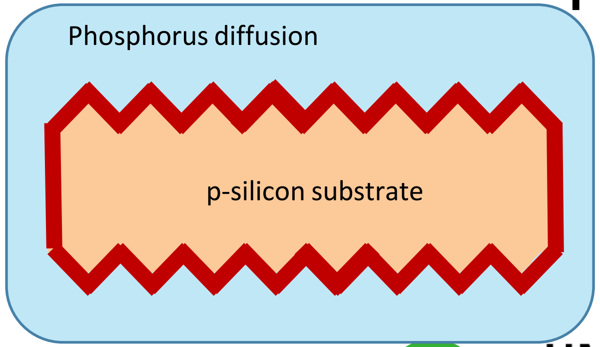


Figure 10.1.3



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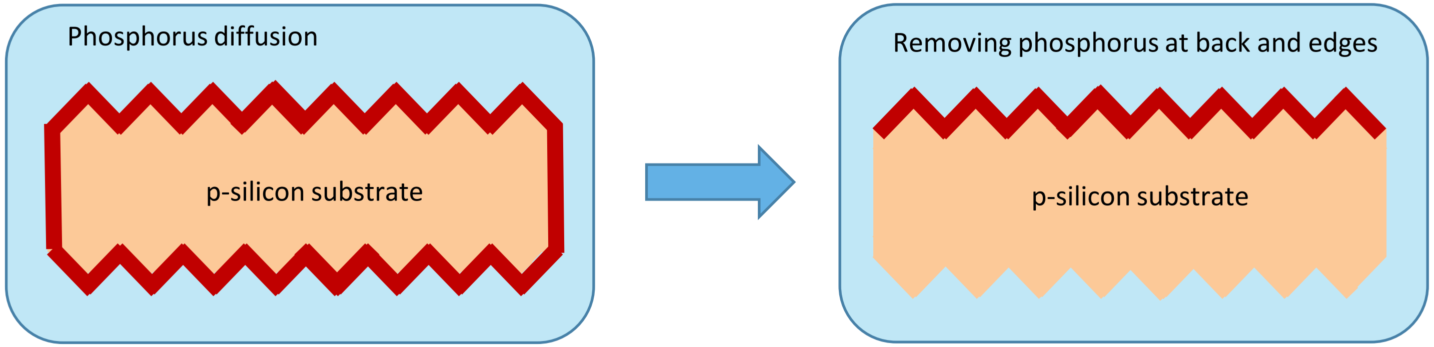
Surface Texturing → Junction Formation → **Emitter Isolation** → Anti-reflection Coating → Screen Printing → Firing

- Attack the bottom side with etchants to remove the n-doped layer
- Etch only one side! “ floating” wafers

Figure 10.1.4



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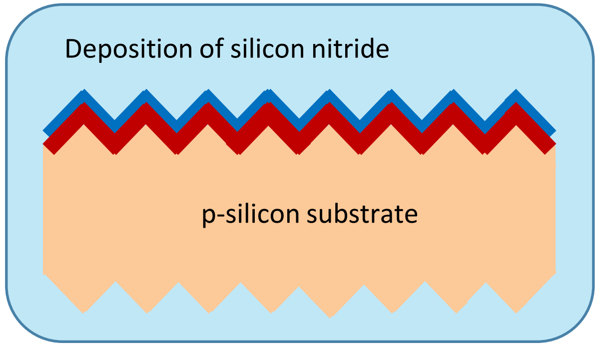
Surface Texturing → Junction Formation → Emitter Isolation → **Anti-reflection Coating** → Screen Printing → Firing

- ARC is applied by plasma-enhanced chemical vapour deposition
- $SiH_4 + xNH_3 \rightarrow SiN_x + \text{gases}$
- Single-sided process (front)
- Refractive index: n = 2.0 - 2.3
- Hydrogen in this process also “cures” recombination centers

Figure 10.1.5



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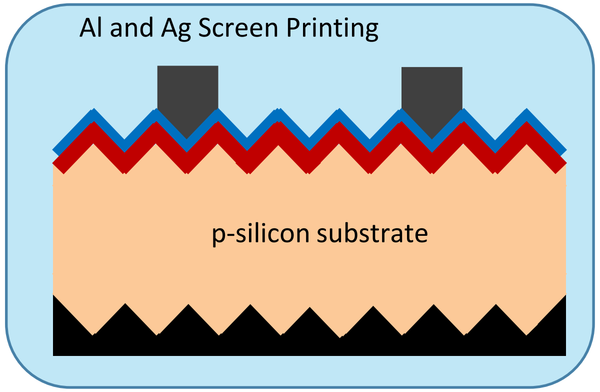
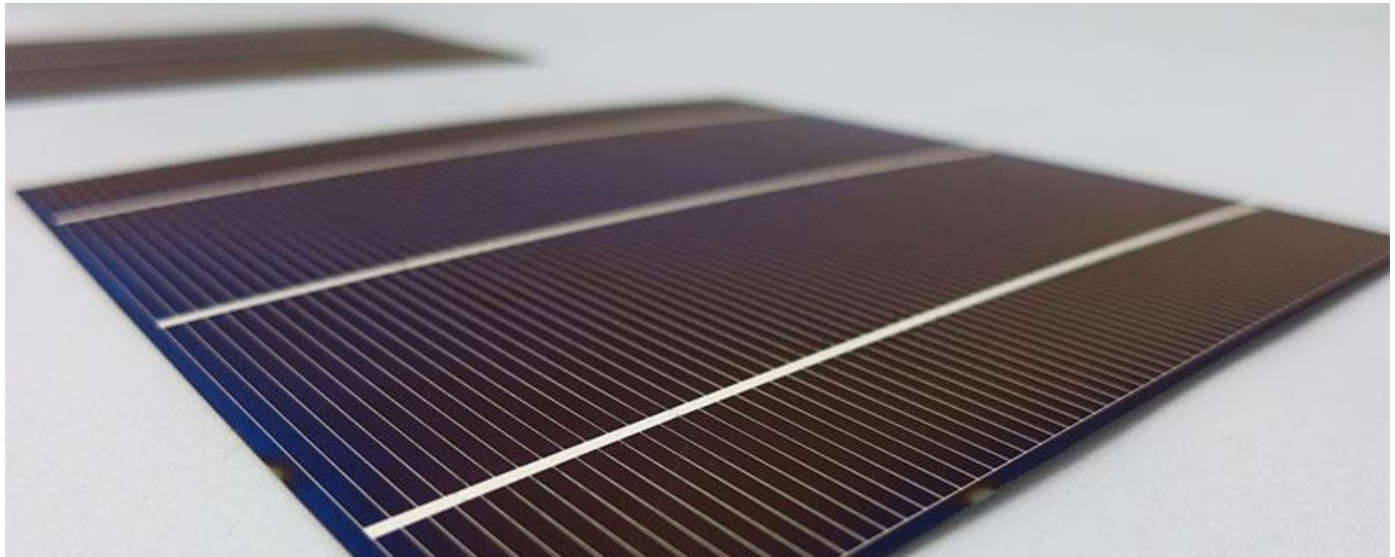
Surface Texturing → Junction Formation → Emitter Isolation → Anti-reflection Coating → **Screen Printing** → Firing

- Rear:
  aluminium paste for rear electrode
- Front:
  silver grid pattern with thin fingers and wide “busbars”





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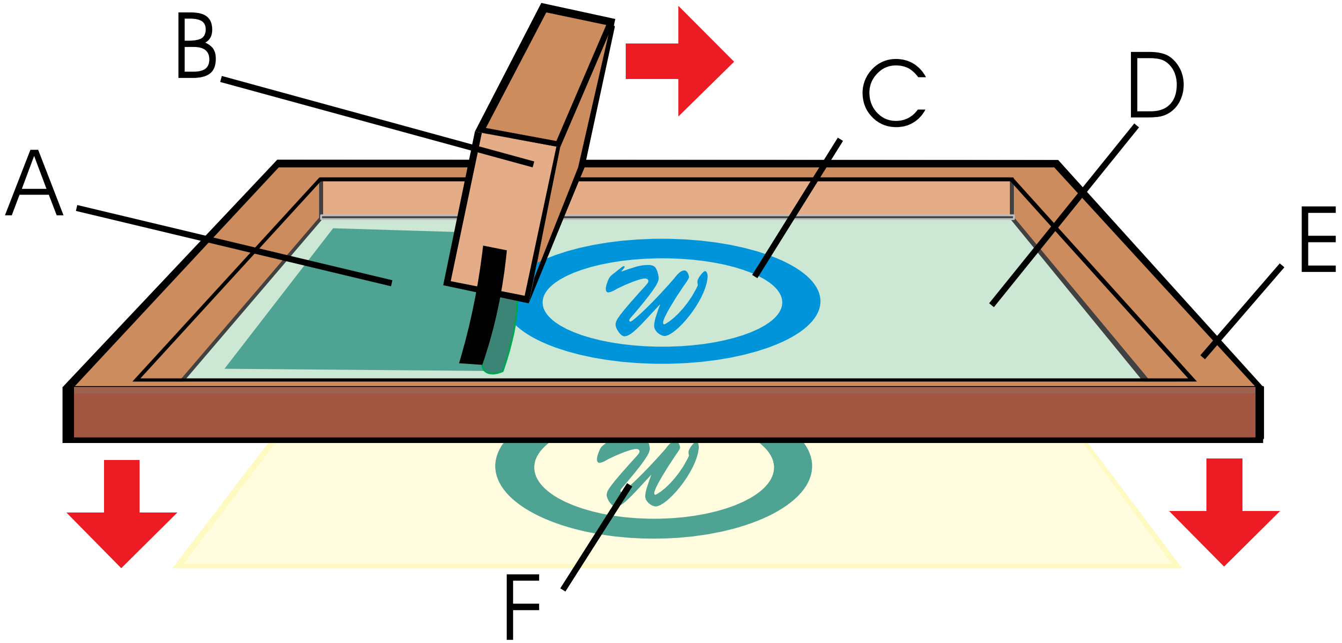
SCREEN PRINTING

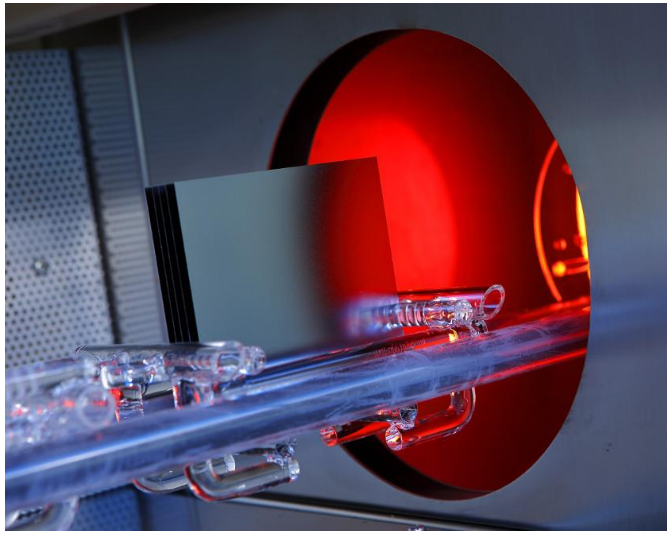
- Fast
- Cheap
- Efficient use of material
- Controlled layer thickness
- Patterns possible
- Lines wider than ~20 µm



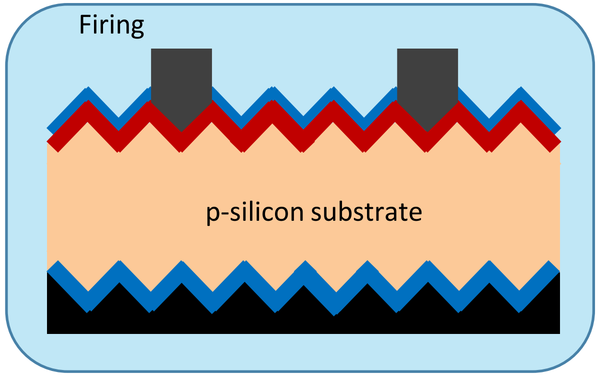
Watch this [screen printing video]

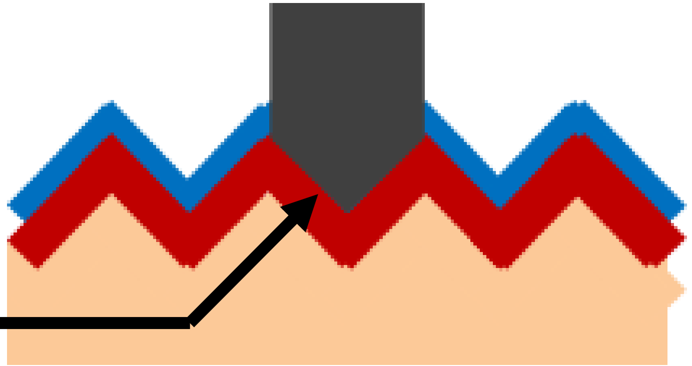
Figure 10.1.6 Screen printer in operation. Source: courtesy of Trina Solar

Surface Texturing → Junction Formation → Emitter Isolation → Anti-reflection Coating → Screen Printing → **Firing**



- **Firing** at 750-870 °C
- Rear: Al diffuses into the wafer creating a p+ doped area (BSF)
- Front: Surface contacts are formed.
- This is tricky!
  The silver paste breaks through the ARC to contact the n-layer.





Blue (ARC) has gone!

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SOLAR CELL FACTORY

Contamination = recombination.
Therefore:

- No dust
- No people
- Conveyor belt transport

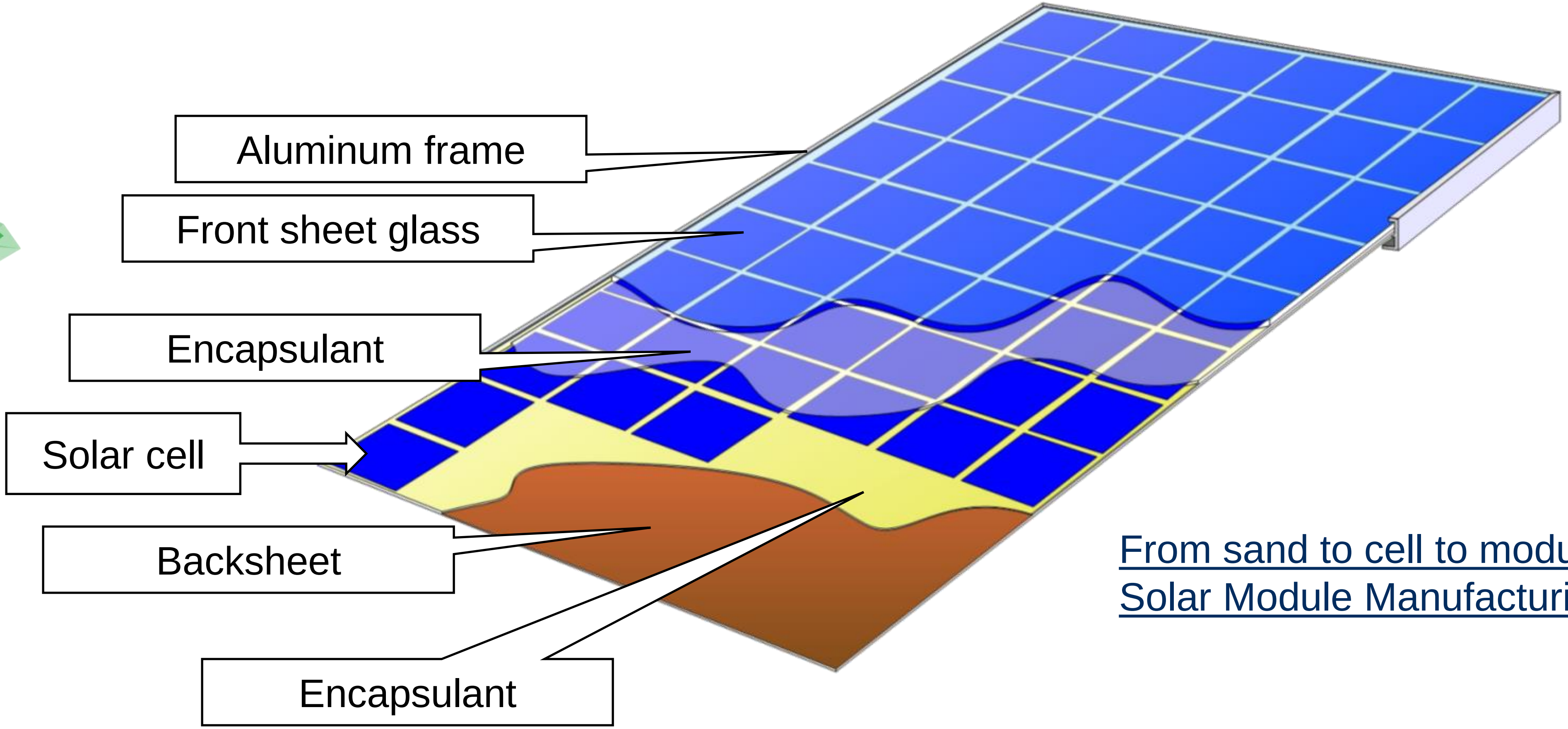
- Equipment often made in NL or USA
- Most solar modules produced in China

- Watch this Youtube video to get a better idea of solar cell production

Figure 10.1.2 A screen-printed silicon solar cell manufacturing facility showing multiple production lines. Source: Courtesy of Trina Solar

4. MAKING SOLAR MODULES

CELLS ARE DONE. LET'S MAKE A MODULE

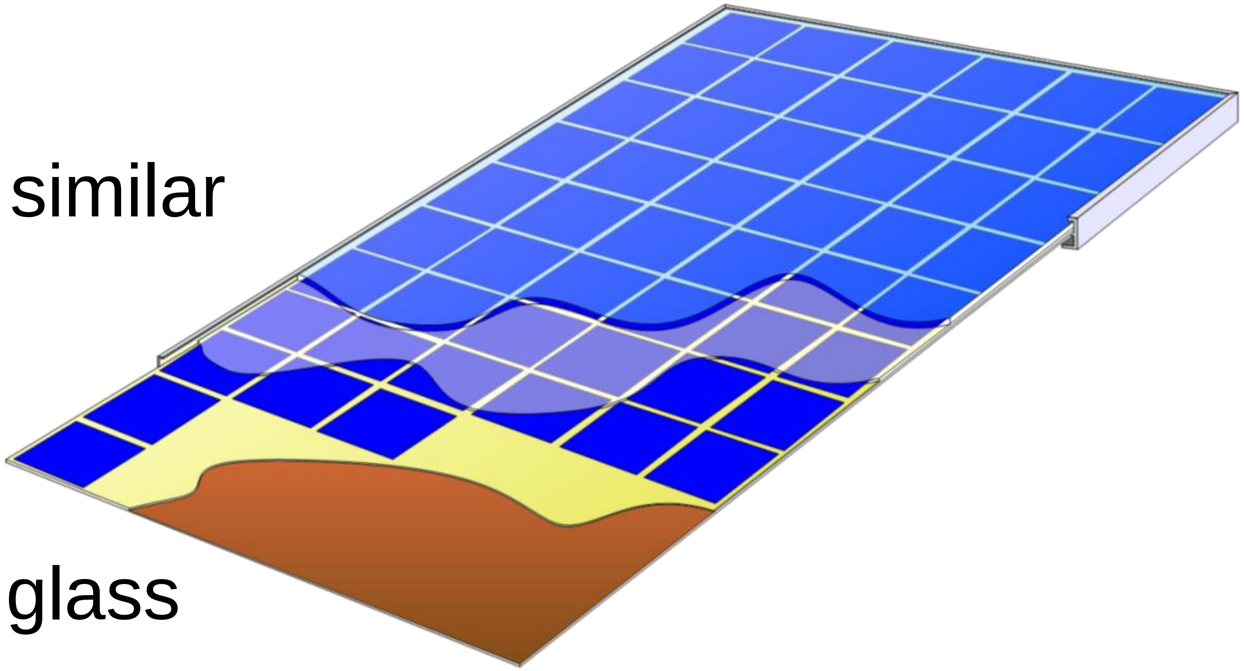


[From sand to cell to module:
Solar Module Manufacturing video (13'38")]

MAKING A SOLAR MODULE

Making a module involves:

- Sort the cells by current – put similar cells into one panel
- Make a string of cells
- Connect strings in series
- Laminate the cells between a glass plate and a backsheet
- Put a frame around it and connect
- Test the panel's output power



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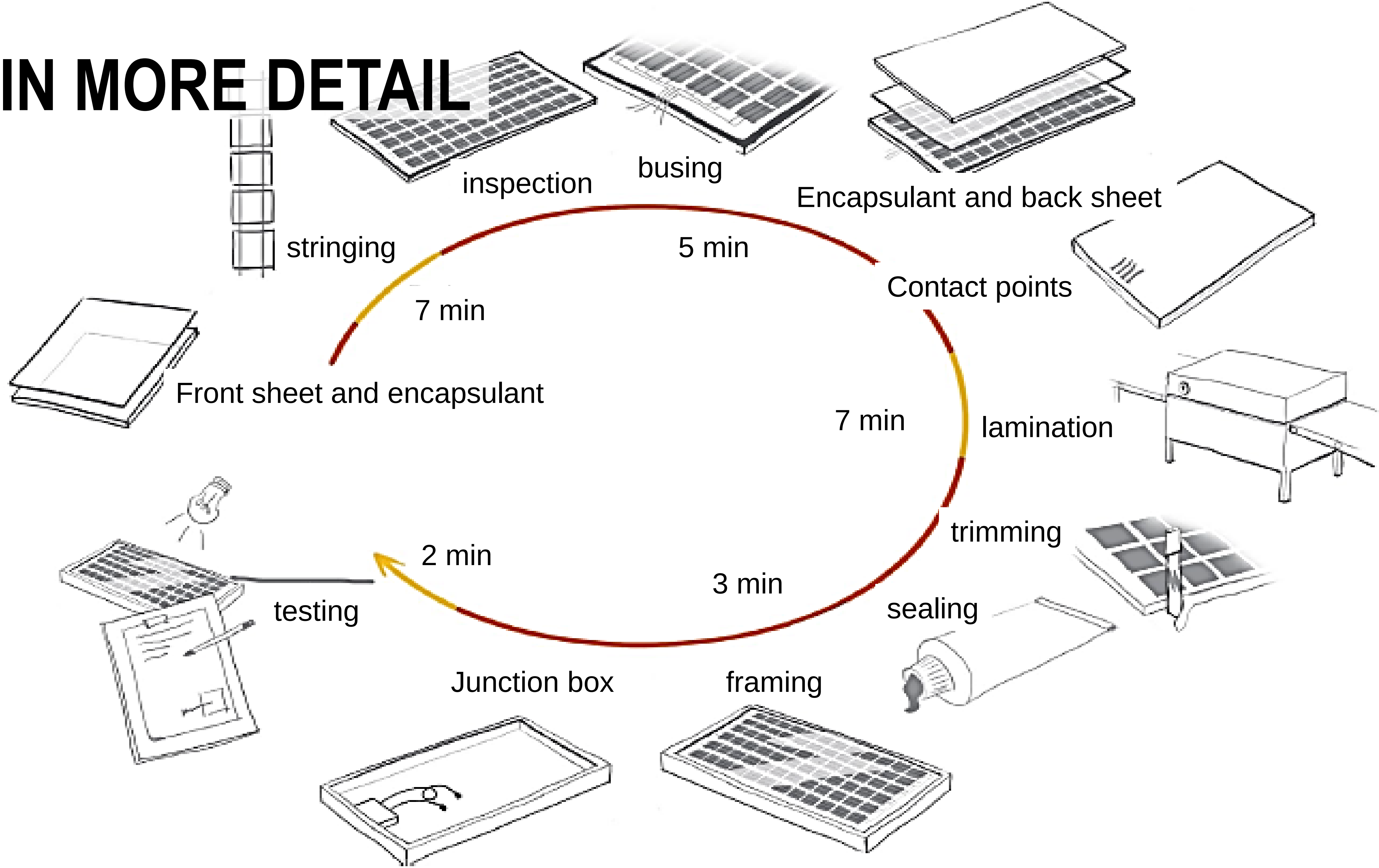
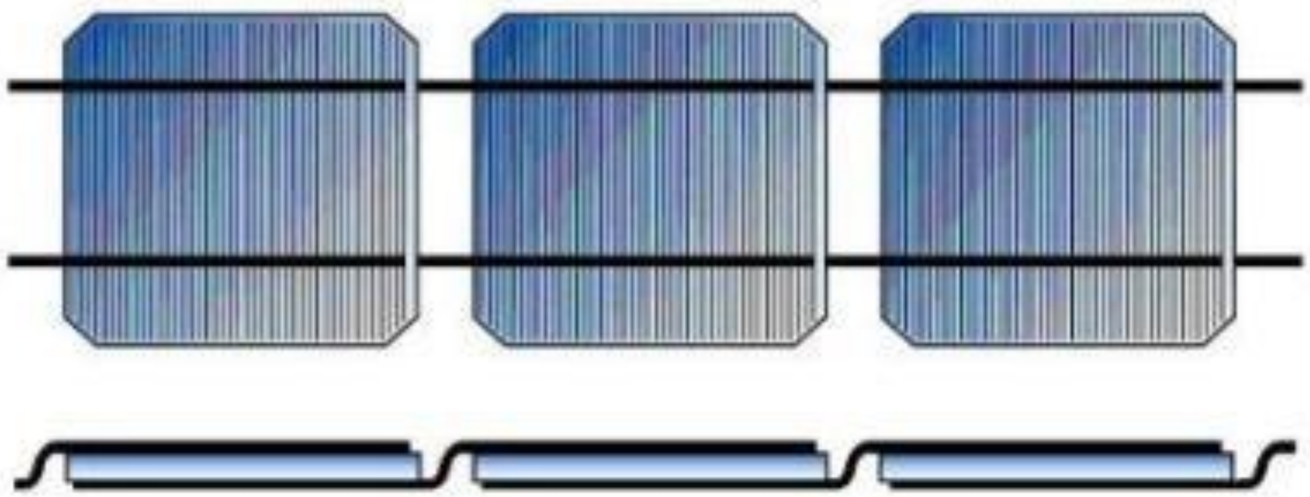
IN MORE DETAIL



CONNECTING CELLS: PHYSICAL

- Daisy chain connection
- Tinned copper strips
- Solder contact

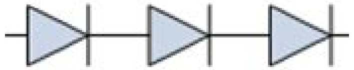


CONNECTING CELLS: ELECTRICAL

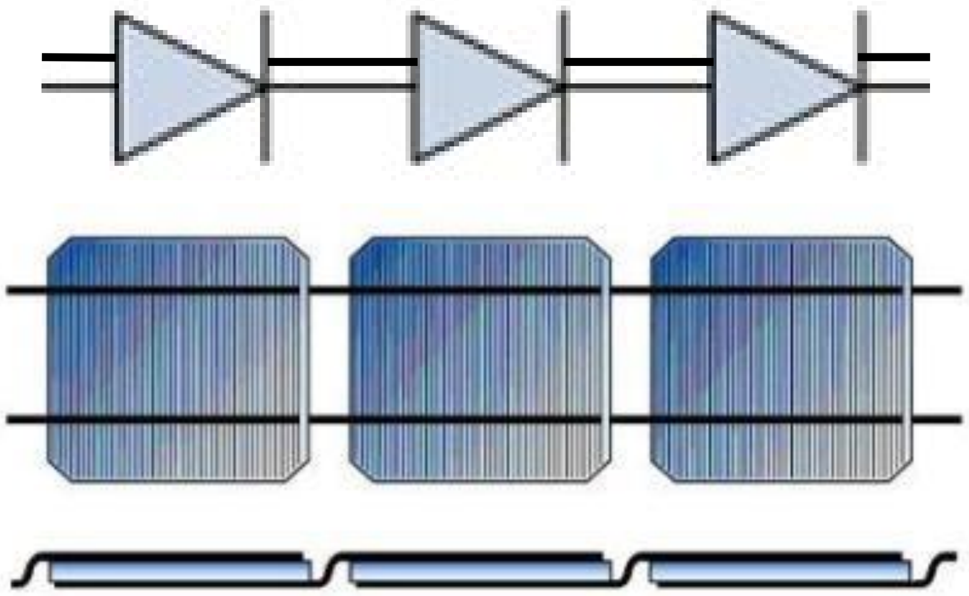
- All diodes in series
- All diodes have the same current (Conservation of charge)
- If the cells have different V_{oc} and/or J_{sc}, the voltage across them will vary
- Then, they are not all at MPP

Consequence: a string delivers less power than the sum of the cells

Symbolic:

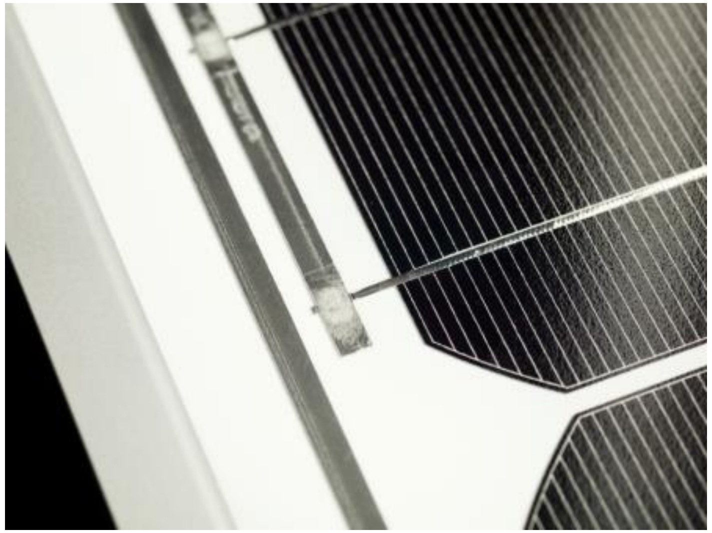


Physical:

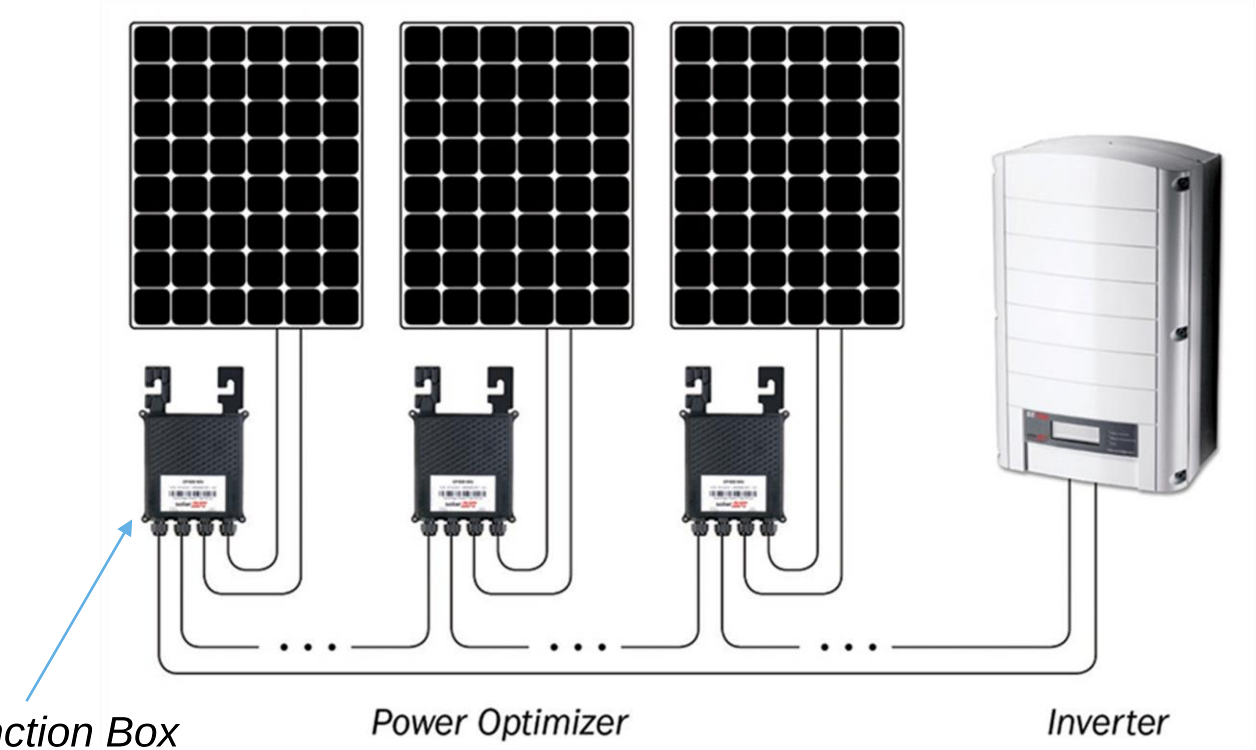


CONNECTING CELL ROWS

- More of the same:
  wide tinned copper strips
- All diodes are in series



- … and panels…



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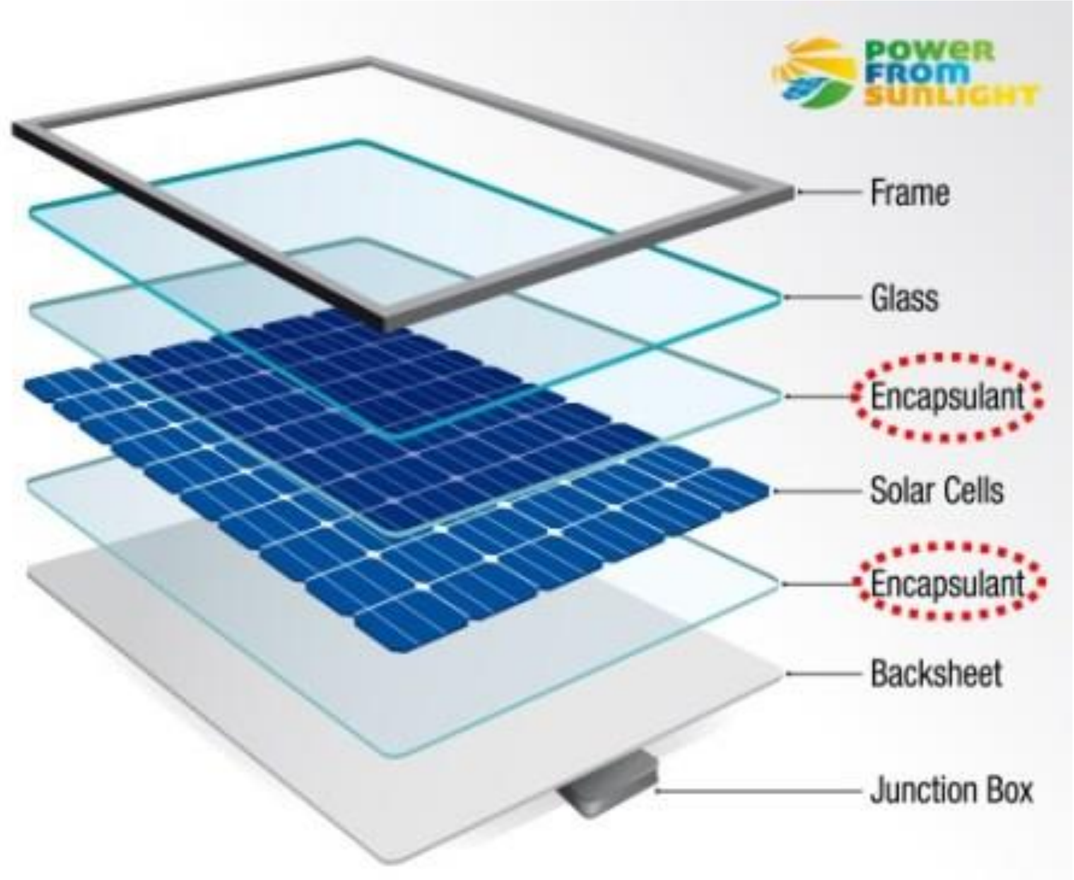
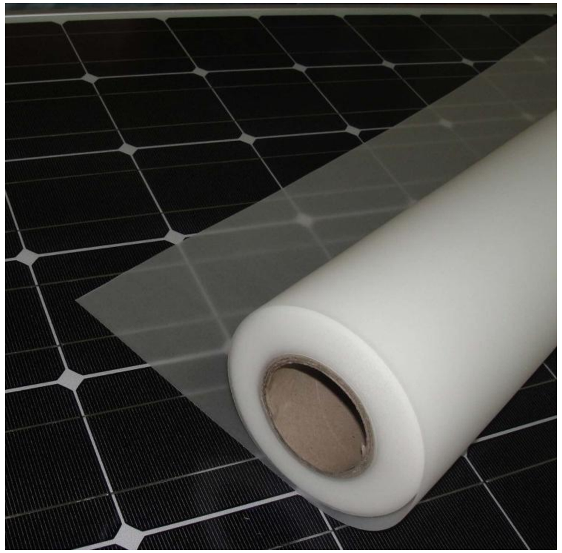
LAMINATION OF THE CELLS



- Stack these layers
- Encapsulant is the ‘glue’
- Most common: EVA



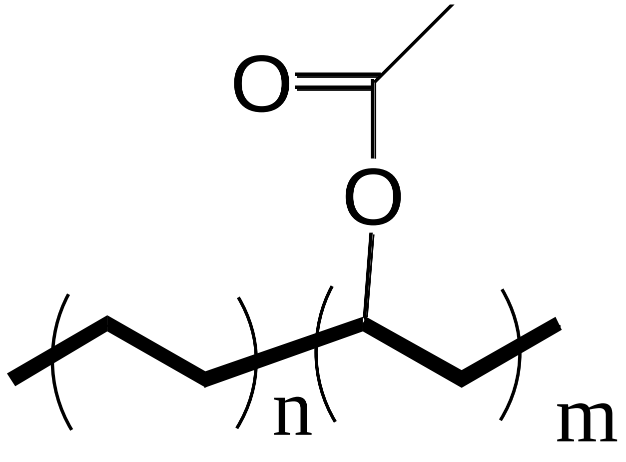
EVA: POLY (ETHYLENE CO-VINYL ACETATE)

Must:

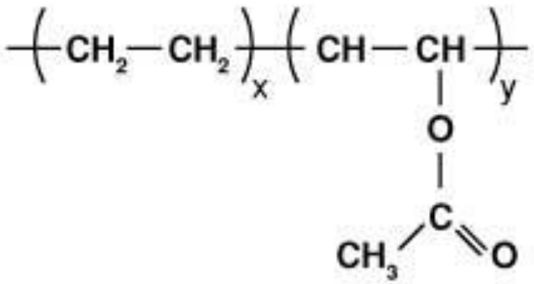
- Hold everything in place
- Absorb differences in thermal expansion
- Protect cells and wires from corrosion
- Be transparent, isolate current

Must endure:

- Temperature excursions
- Humidity, water, salt
- UV irradiation



Ethylene Vinyl Acetate



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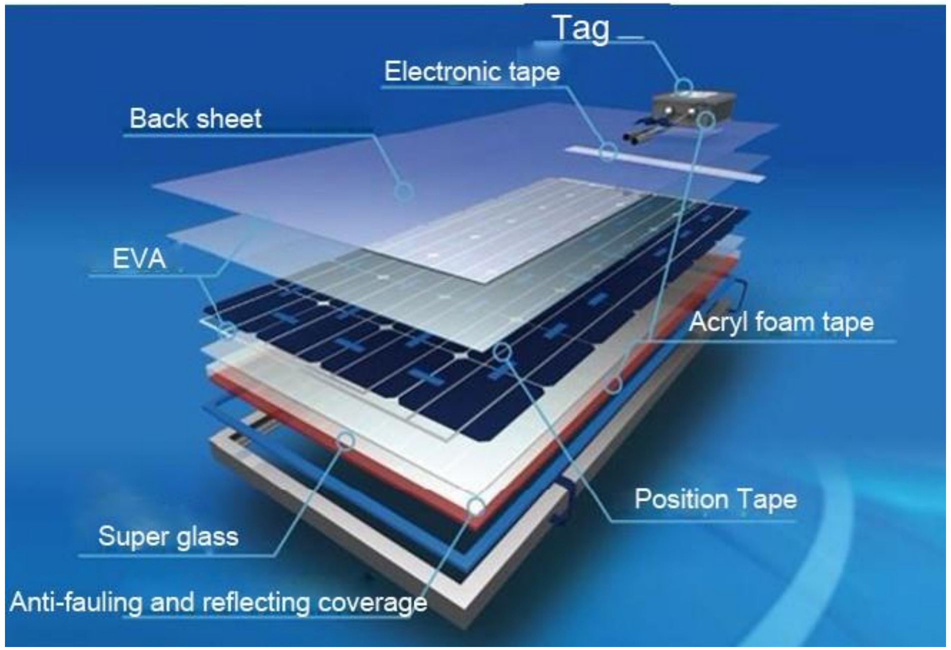
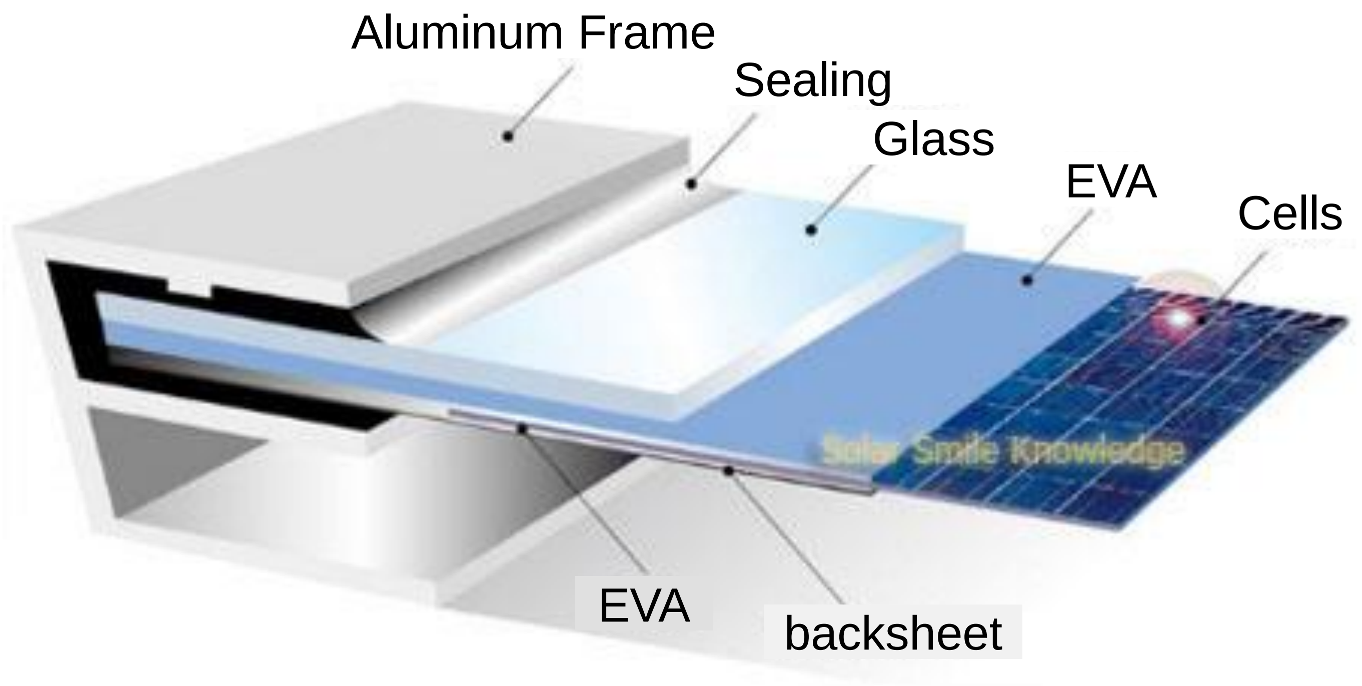
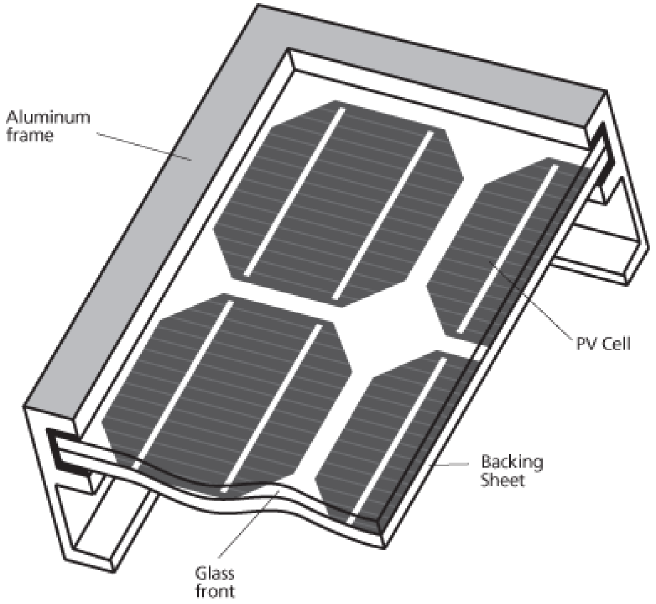
EVA: THE PROCESS

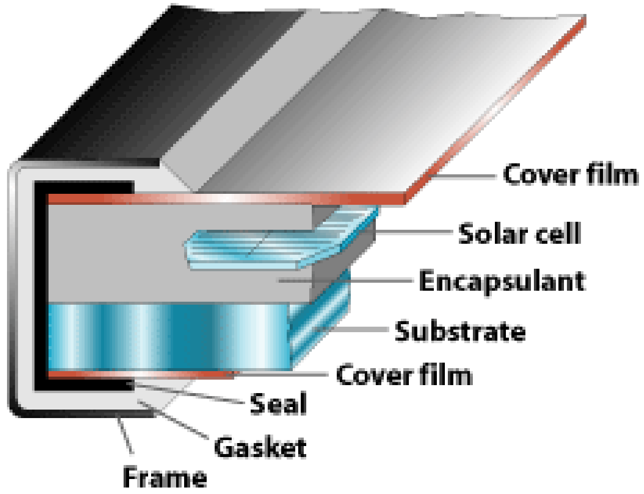
- The material melts at 45-65 °C
- The polymer crosslinks around 140 °C within 2 minutes



THE SUPPORT FRAME







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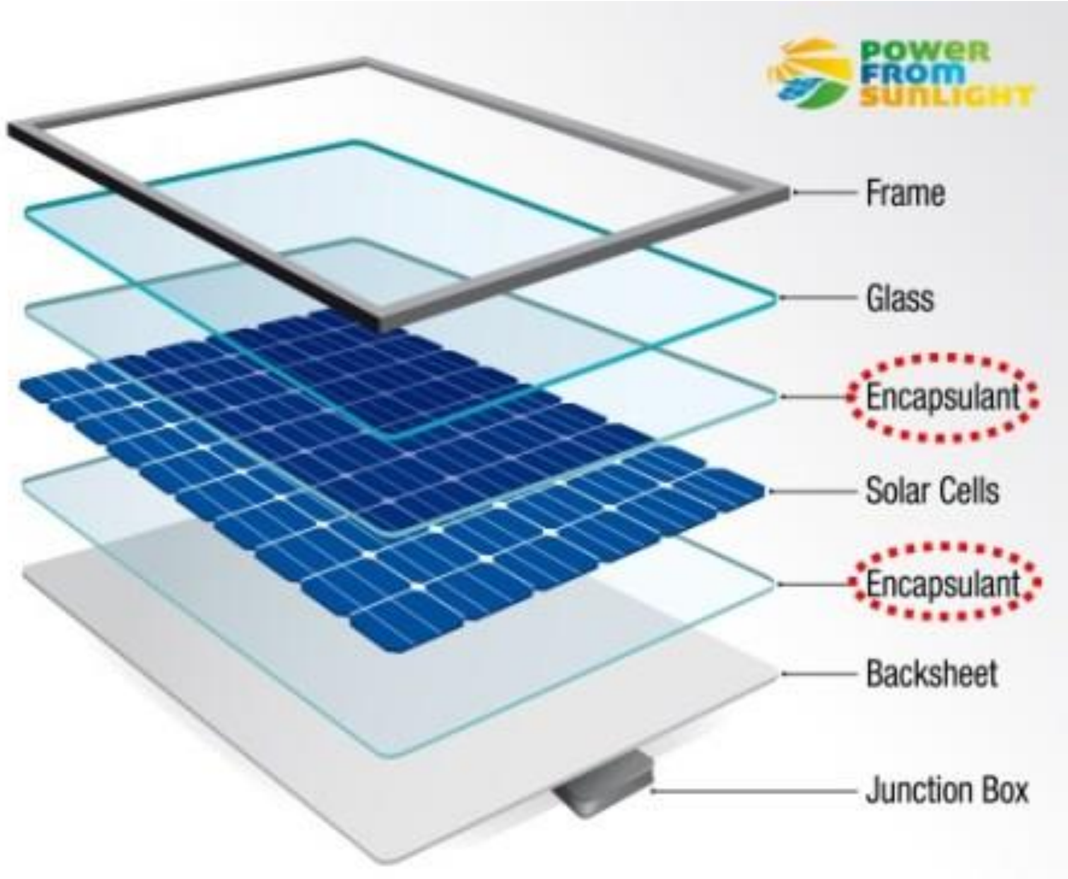
THE BACKSHEET

Traditional solution:

Tedlar®: brand name for poly vinyl fluoride (PVF)

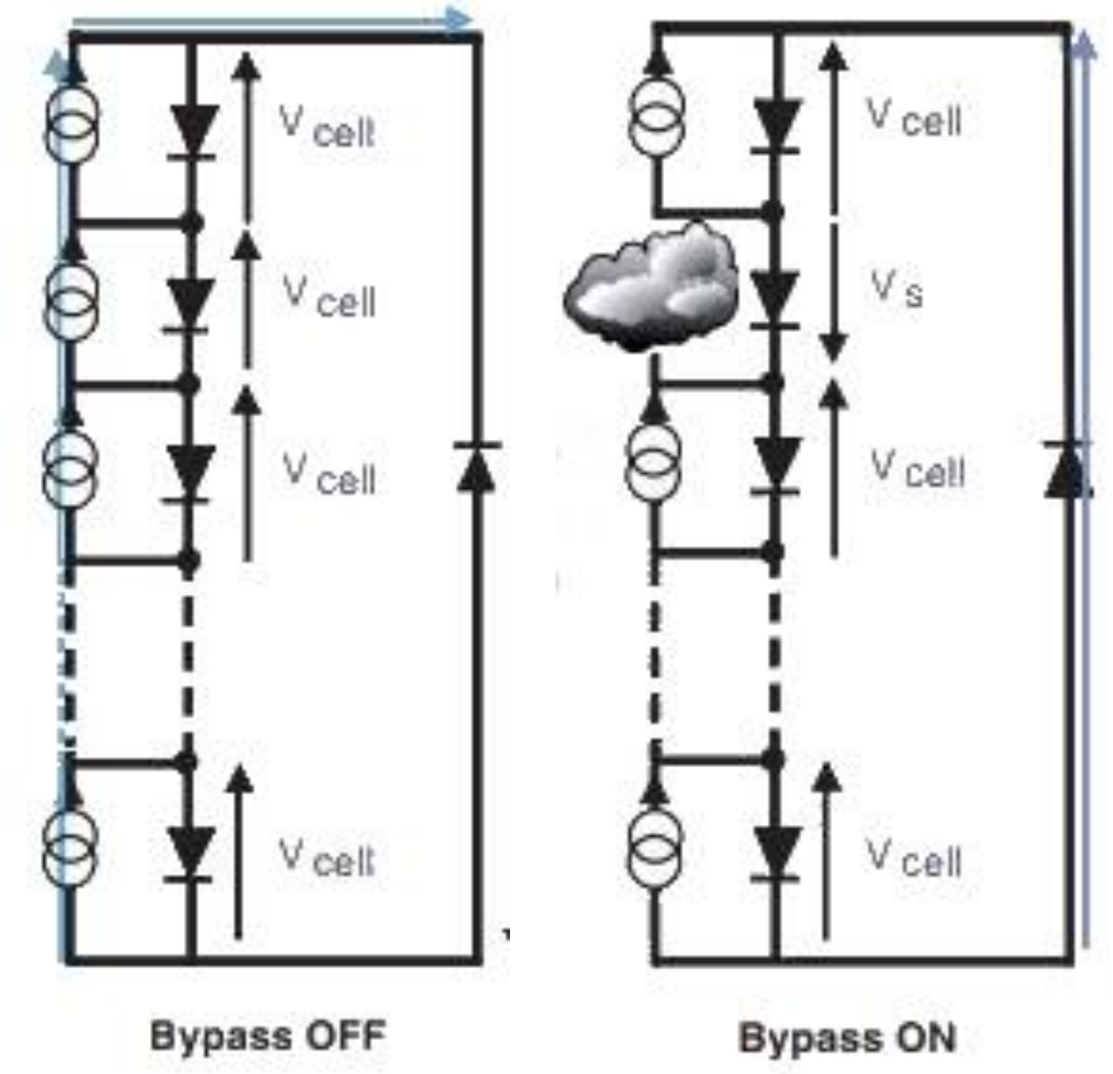
Thermoplastic material:

- high weather-resistance
- high strength
- low permeability of moisture, vapor, oil
- *T* between -70 °C to +110 °C



THE BYPASS DIODE
IN THE JUNCTION BOX

- All cells should produce the same current
- If one does not… it gets stress from the neighbours
- The bypass diode protects a shaded solar cell against damage



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WRAPPING UP

The cell:

- Texturing
- Phosphorus diffusion
- Removing backside phosphorus
- Antireflective coating
- Al and Ag screen printing
- Firing

The module:

- Front sheet and encapsulant
- Busing
- Encapsulant and backsheet
- Connections
- Lamination
- Trimming, sealing, framing
- Junction box and test

7. TIME FOR A BREAK