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Solar Array Materials and Manufacturing

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Reliability Engineer

Solar Array Requirements: Manufacturing

- Safety first
- Output maximum power (for minimum weight and aerodynamic losses)
- Maintain power for the required life of the car

OSU Phoenix in 2013

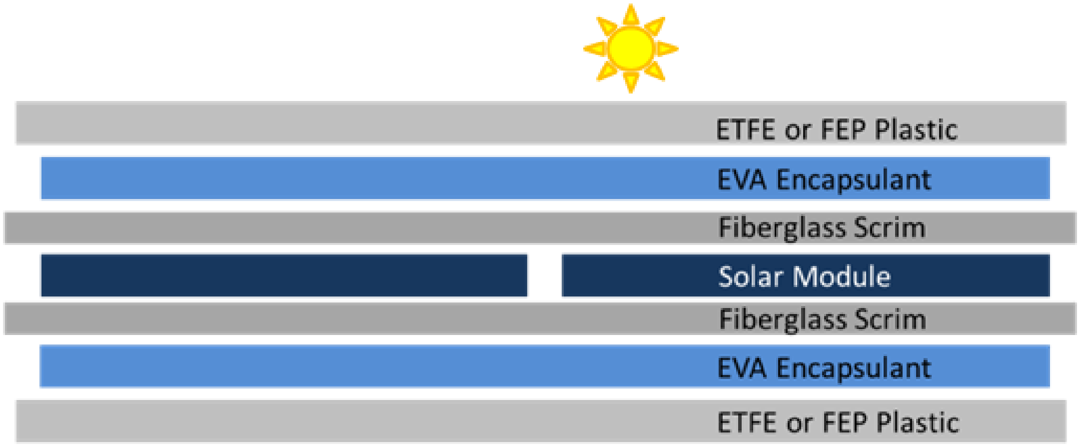
INTRODUCTION

Safety

- Include safety in every plan
  - Personal Protective Equipment (PPE) (safety glasses, Arc Flash gear, HV gloves, etc.)
  - Refer to NFPA 70E Table 130.7(C)(15)(b) for PPE requirements according to the possible voltages and amperages you may encounter
  - Current as low as 7mA can be deadly
  - Work in pairs in case there is an emergency
  - Rubber mats reduce the chance of you being the conductor to the ground
- Create a Job Hazard Analysis where you understand what can go wrong and how you are going to avoid it by work processes and or by PPE
- Don’t touch the live electric conductors
  - Disconnect and lock out/ tag out any power sources
- Solar panels are energized in sunlight.
  - Don’t wire or make connections on your array in the sun, cover with an opaque blanket or work inside (not just a tarp!); even at very low irradiance your array will output enough voltage and current to be dangerous
- Use sufficient wire gauges for your array current
- Use ventilation for soldering
- Engineer out the possible hazards - use easily accessible quick disconnects for rapid shut down
  - Always think what is the worst thing that can happen and engineer for that

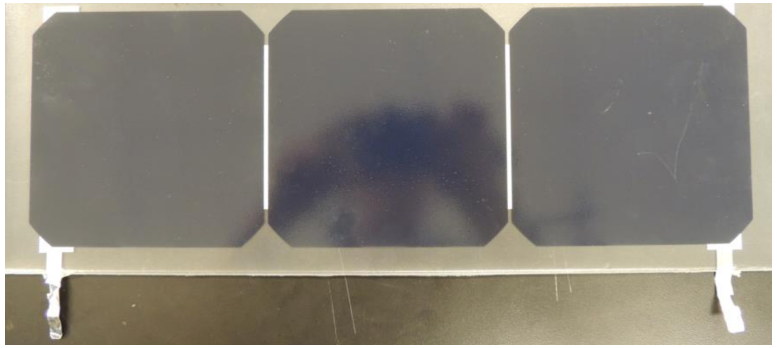
SOLAR MODULE MATERIALS AND METHODS

Solar Module Lamination Stack



Front Sheet
Encapsulant
Fiberglass scrim (optional)
Cells/interconnects
Fiberglass scrim (optional)
Encapsulant
Back Sheet

Solar module sandwich



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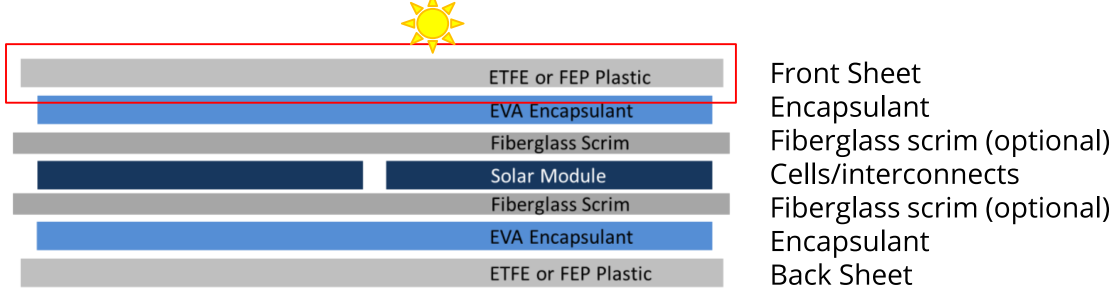
MATERIALS

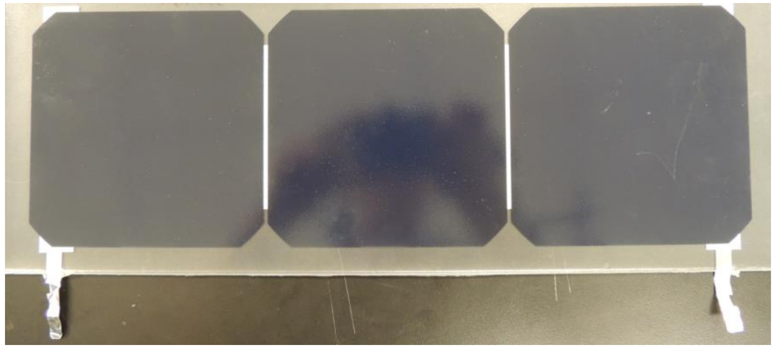
Front Sheets

Get something you can wash

- PET
  - Index of refraction 1.6+ (shiny, more reflection)
  - Thicker, stiffer, protects against cracking
  - Can match physical properties of backsheet
  - Will embrittle in the sun (after a few years)
  - More scratch-resistant
- Fluorinated polymers
  - Index of refraction down to 1.35 (less reflection)
  - Usually thin, expensive
  - May scratch during cleaning
- Anti-reflective coated front sheets
- Many other options
- One side of your front sheet will be pre-treated for adhesion- make sure you glue to the right side (Sharpie test)
- It is best to pre-treat your front and back sheets before lamination by running them through the laminator once to perform any initial shrinking that they might do



Solar module sandwich



$$R = \left| \frac{n_1 - n_2}{n_1 + n_2} \right|^2$$

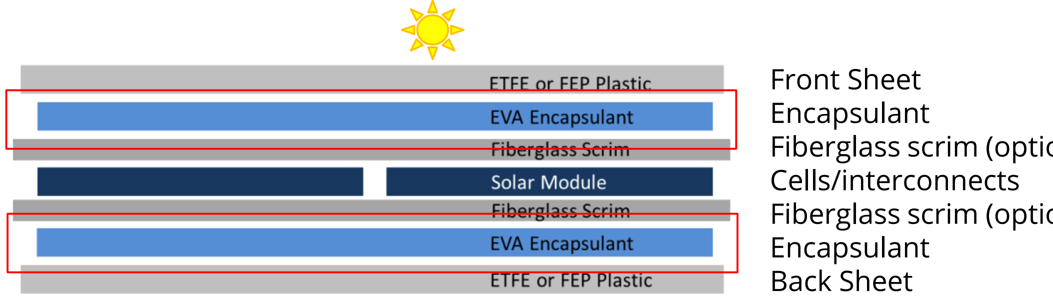
Fresnel equation for reflections at normal incidence

$R_{PET} = ((1.65-1)/(1.65+1))^2 = 6\%$

$R_{FEP} = ((1.35-1)/(1.35+1))^2 = 2\%$

MATERIALS

Encapsulants- use a solar film



Solar module sandwich

- EVA- common, cheap, works fine especially the newer materials with stabilizers
- POE- not as common or cheap, but not that much more expensive, probably overkill for this application
- Silicones- nice, but may require different processing. Only use acetate-free silicones.
- Others (thermoplastic, thermoset, etc)- thermoset preferred for higher temperature applications
- Cut your EVA to just larger than your cell area (5mm border on each side recommended) and cut your backsheet/frontsheet materials to just larger than your EVA
- In general
  - Yellowing likely won't be an issue for you if you use a solar module encapsulant (fiberglass + epoxy not the case!)
  - If you can get it to laminate without bubbles, delams, etc. then it will probably work out for your race
  - If your array voltage is relatively low (<200V) and you are using polymer front/backsheets then you don't need a high resistance encapsulant
  - 200-450 μm is common range for thicknesses. Thicker protects more against cell cracking, thinner is lighter.

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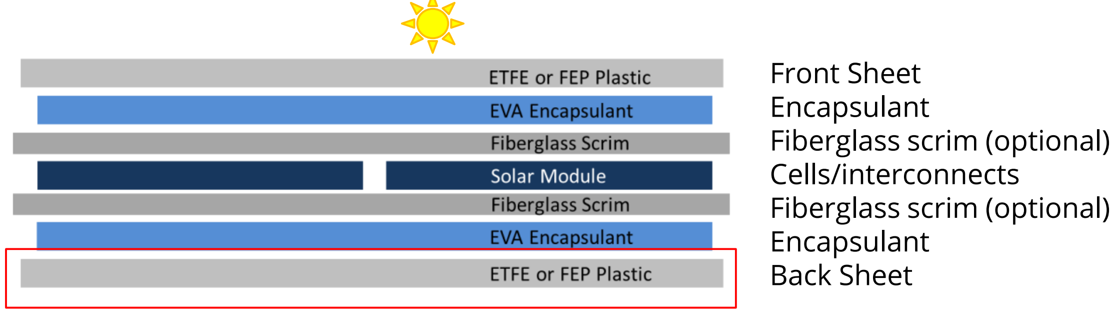
MATERIALS

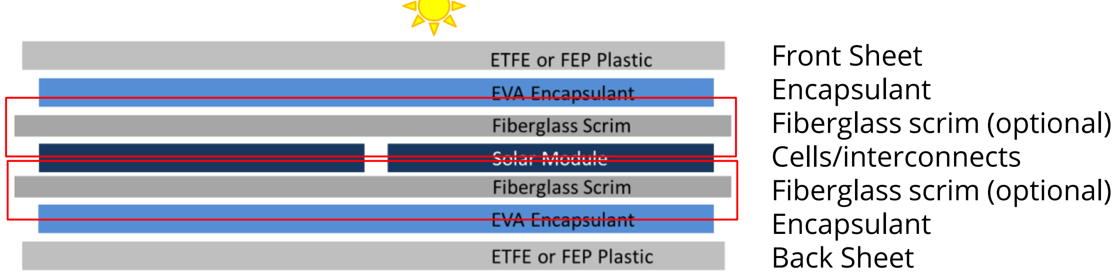
Backsheets



Solar module sandwich

- PET
  - Very common in industry, inexpensive, strong
- ETFE or other fluorinated polymer
  - May be thinner, lighter, more expensive, easier to rip/tear/cut
- Aluminum (I've seen this used!) is unnecessary
- Glass (unnecessary)
- If the front sheet and the back sheet have similar thickness then you will see less cell cracking when the modules are bent.
- It is best to pre-treat your front and back sheets before lamination by running them through the laminator once to perform any initial shrinking that they might do

Optional: Fiberglass Scrim



Solar module sandwich

- If your modules are coming out with bubbles inside you can add fiberglass scrim material around the cells to help air escape during lamination
- Might also improve mechanical robustness
- Not required if you have a great laminator

Craneglass 230, an appropriate non-woven, 0.005” fiberglass scrim

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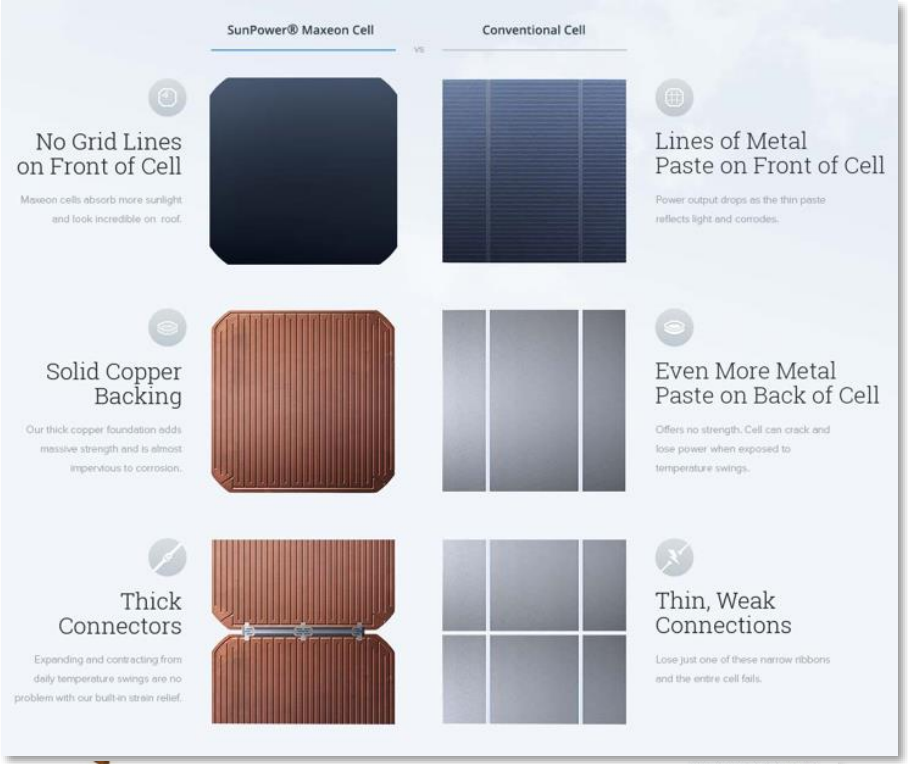
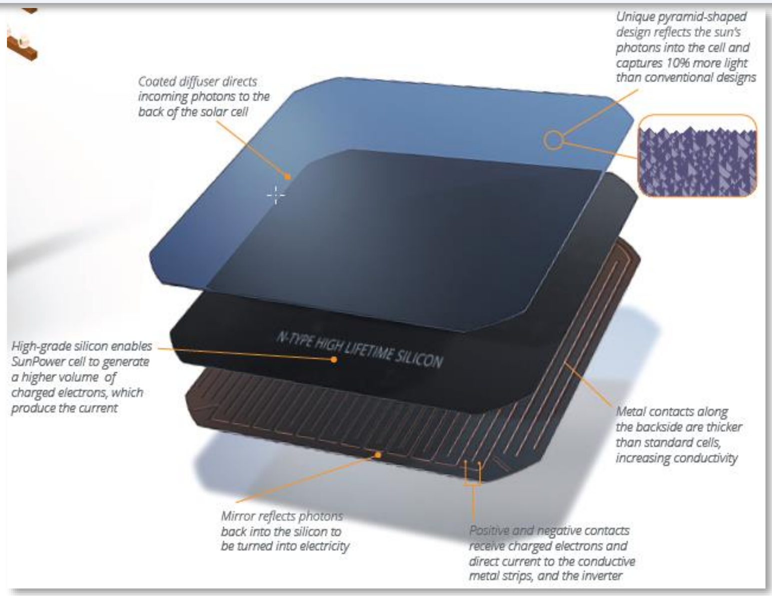
Materials: Cells and Interconnects

- Recommended: SunPower Maxeon Interdigitated Back Contact Cells and I-tab interconnects
- Use the right ribbon to solder to your cells
  - For front contact cells, use flat tin-coated Cu ribbon
  - Large enough for your current
  - Strain-relieve your interconnections (See Z-shape below)

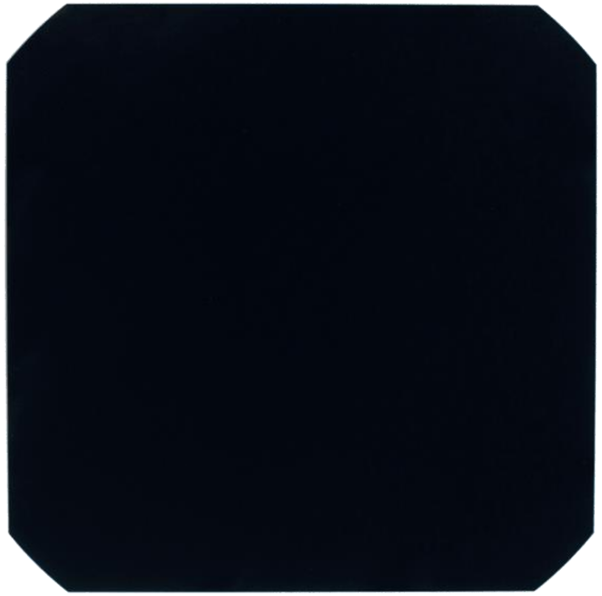


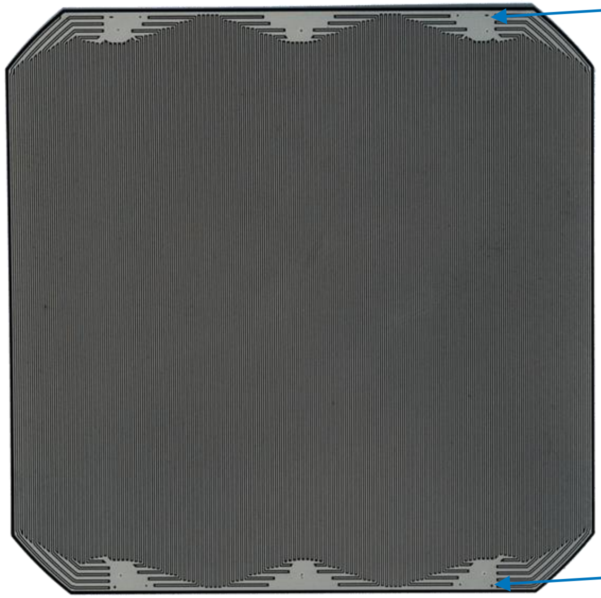


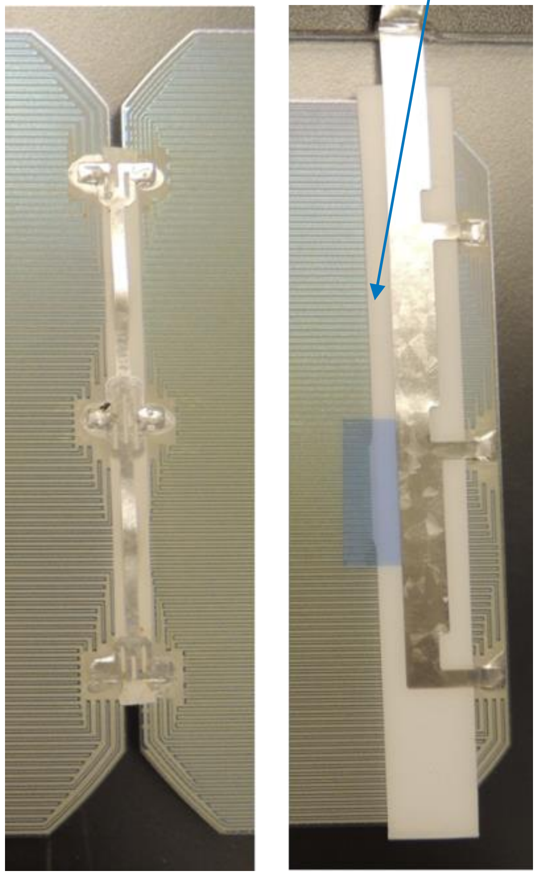
Front contact series connection of two cells, cross section

Interconnects: SunPower Maxeon Cells

- Maxeon cells are labeled with little + and – designations
- The fingers on the back alternate + and –
- Do not let metal parts cross the fingers without insulation
- Never use a non-strain-relieved ribbon to solder Maxeon cells







https://pv-manufacturing.org/all-back-contact-solar-cells/

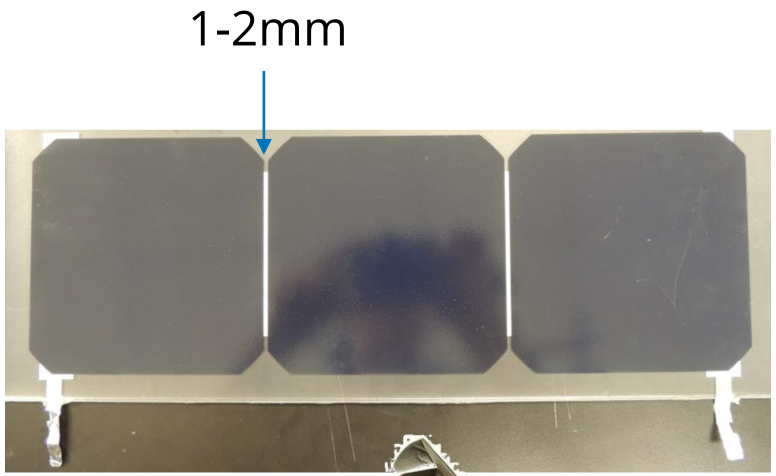
MATERIALS

Solder paste, flux

- Soldering ribbons to cells can be made easier by adding solder paste, solder, or solder flux.
  - Paste can be added between the cell and ribbon or on top the ribbon.
  - Flux cleans oxidations off surfaces of metal. Solder promptly, as the flux will evaporate and surfaces will oxidize in the air after some number of minutes
  - Melted solder helps heat flow by increasing surface area of contact between soldering iron and workpiece
- SunPower Maxeon cells are made for use with lead-free solder paste, though leaded will also work
- No-clean flux is usually fine, but if you use a lot of it then it can affect your lamination
- Non-no-clean flux *must* be cleaned very thoroughly before lamination or it may cause degradation of your modules. I don’t recommend using it.
- Leaded solder, solder paste melts around 183°C; do not use leaded solder or solder paste if your lamination temperature is over 158°C due to temperature non-uniformities

DESIGN

Cell Spacing and Soldering



- Cell-cell and string-string spacing 1-2mm is standard in industry, dictated by repeatable distance for manufacturing that results in not shorting adjacent cells
- Larger modules are easier to string after installation, but harder to manufacture and install
- Always use strain relief; use SunPower I-tabs with SunPower Maxeon cells and strain-relieved flat tinned copper ribbon with front contact cells.
- Thinner, wider ribbon results in less cell cracking in lamination
- More copper adds weight, but reduces temperatures for high current applications

Ribbon between 2 front contact cells has strain relief

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METHOD

Soldering

- Chisel or hoof tips- something with a lot of flat surface area
- Apply solder paste between cell and ribbon/tab
- Solder with maximum area of contact. You can practice by burning a piece of paper with your soldering tip
- Solder fast and hot: 375°C -400°C should work
- Destroy some solder bonds by hand and make sure they are strong, you aren’t burning the cell’s metallization
- Practice!
- Keep your solder joints smooth- peaks of solder can break cells in lamination

Chisel Tip

Hoof Tip

Burn marks on paper for practicing holding the soldering iron at the right angle for maximum contact

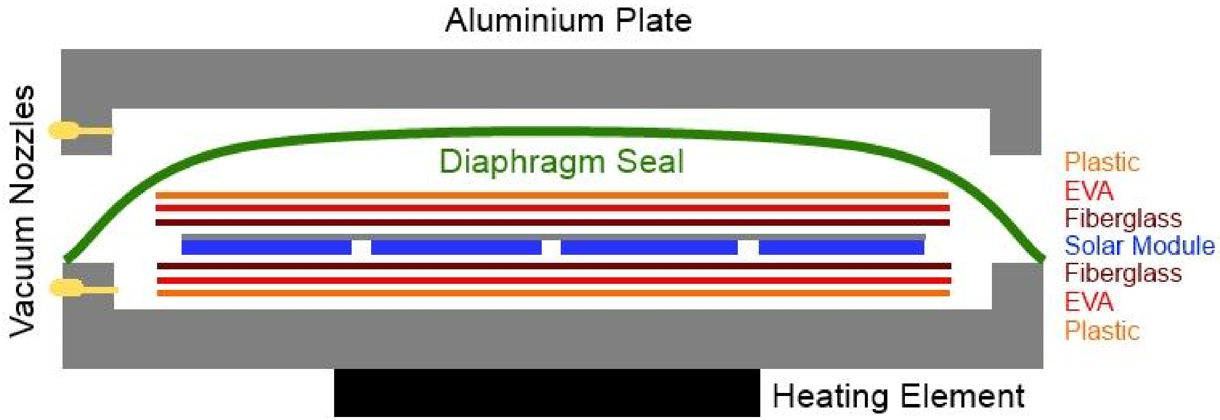
How to Get Your Ribbons Through the Back Sheet

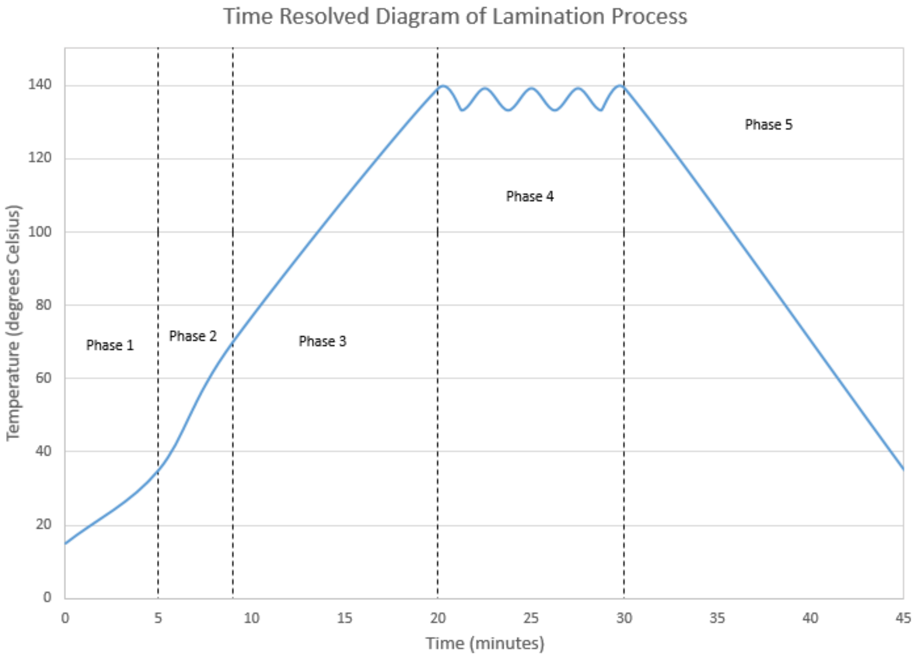
- Cut a hole (circle, square, whatever) in backside encapsulant and backsheet. The hole should be a little larger than the ribbon.
- Feed ribbons out the hole
- After lamination, pull ribbons up so they are perpendicular to laminate, solder to your connecting wire
- Protect against strain, moisture, and exposed voltage using an acetate-free silicone RTV, such as PV-804. You can also use a waterproof heat shrink.

METHOD

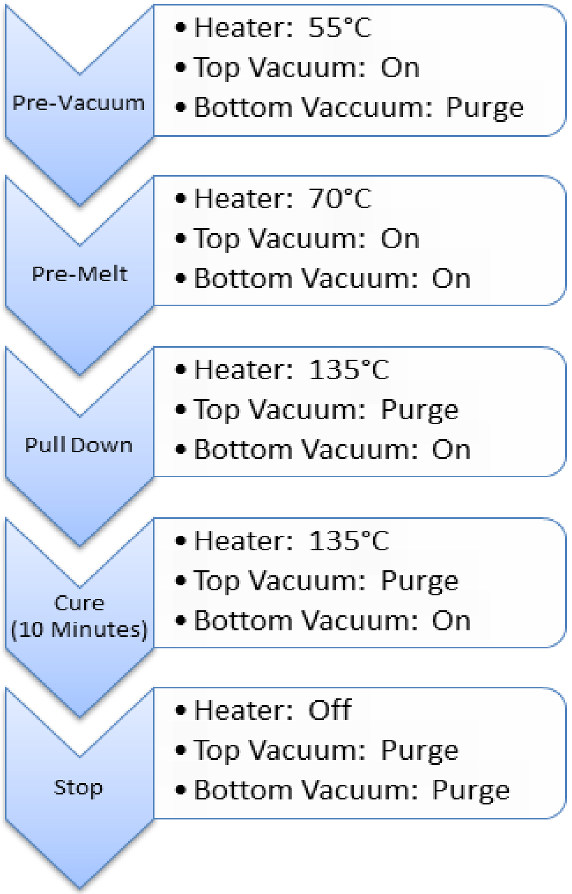
Lamination

- If you can, use a professional laminator
- Follow cure profile for your encapsulant
- Normally laminate face down





Example lamination profile



Common EVA lamination schedule, according to the STR EVA manual

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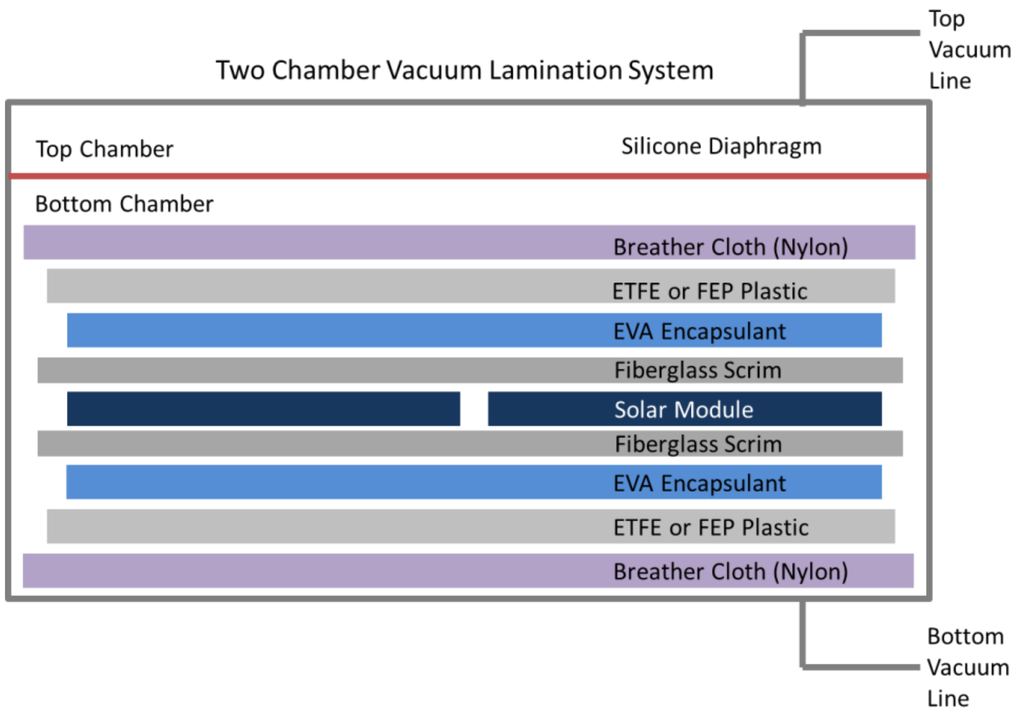
METHODS

Troubleshooting Lamination

- Bubbles in laminate
  - Improve vacuum during pre-melt and pull down phase
  - Add nylon breather cloth above and below module
  - Add fiberglass scrim inside module
- Cell cracking
  - Ensure encapsulant is thick enough and soft enough before pull down phase
  - Eliminate peaks of solder on solder joints
  - Clean non-uniformities out of laminator



PERFORMANCE AND RELIABILITY

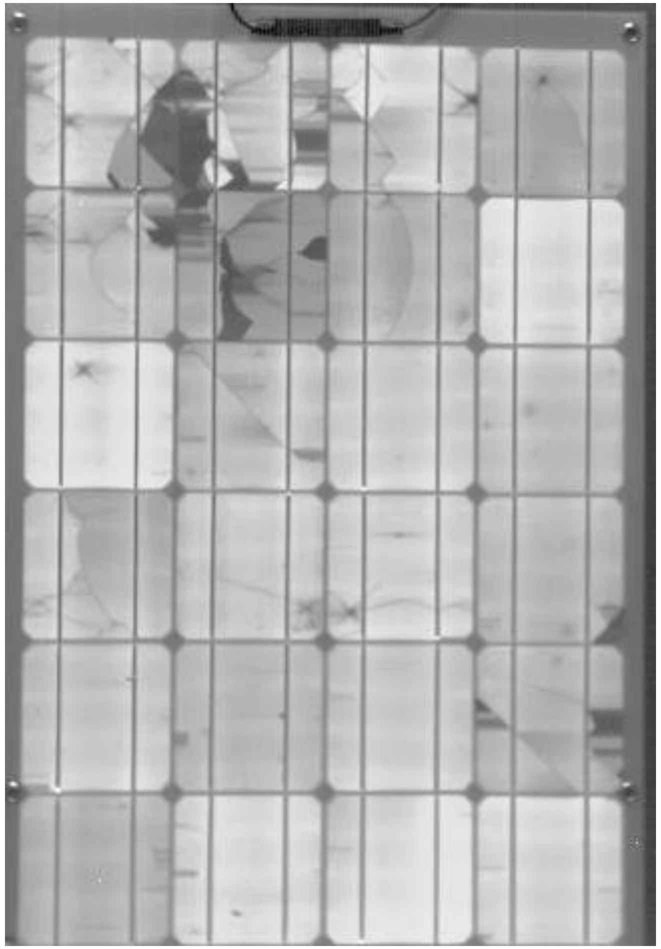
Maximum Power- An Overview

- Use high efficiency cells (SunPower Maxeon is a great choice)
- Uncracked cells (SunPower Maxeon are harder to break)
- Current matched strings
- Sufficient power trackers for your geometry
- No stringing-induced shorts- figure out where your p/n junction is and don't add solder across it or melt it with a laser
- Bypass diodes for geometry/shading non-ideal conditions
- Lamination materials as transparent as possible
  - Minimal reflections at interfaces
  - No coloration
- Lowest operating temperature possible
- Make extra panels for replacement in case of damage

Our team using a short sniffer to identify the location of sloppy soldering-induced microscopic solder pieces shorting fingers on the backside of an IBC cell

Reliability Concerns

- Broken cell-ribbon or ribbon-wire solder connections
- Vibration-induced breaking of joints/wiring/cells/modules
- Cables or ribbons broken by hinging of insufficiently-stranded ribbons or cables
- Lamination materials yellow or become soiled/cloudy/scratched
- Cell hot spots from mismatched current



Electroluminescence image of a random Amazon flexible panel upon arrival

Your array doesn't need to have the same reliability standards as a 30 year solar module, but you can still learn a lot from the designs, materials, and processes that have been developed for traditional modules.

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BYPASS DIODES

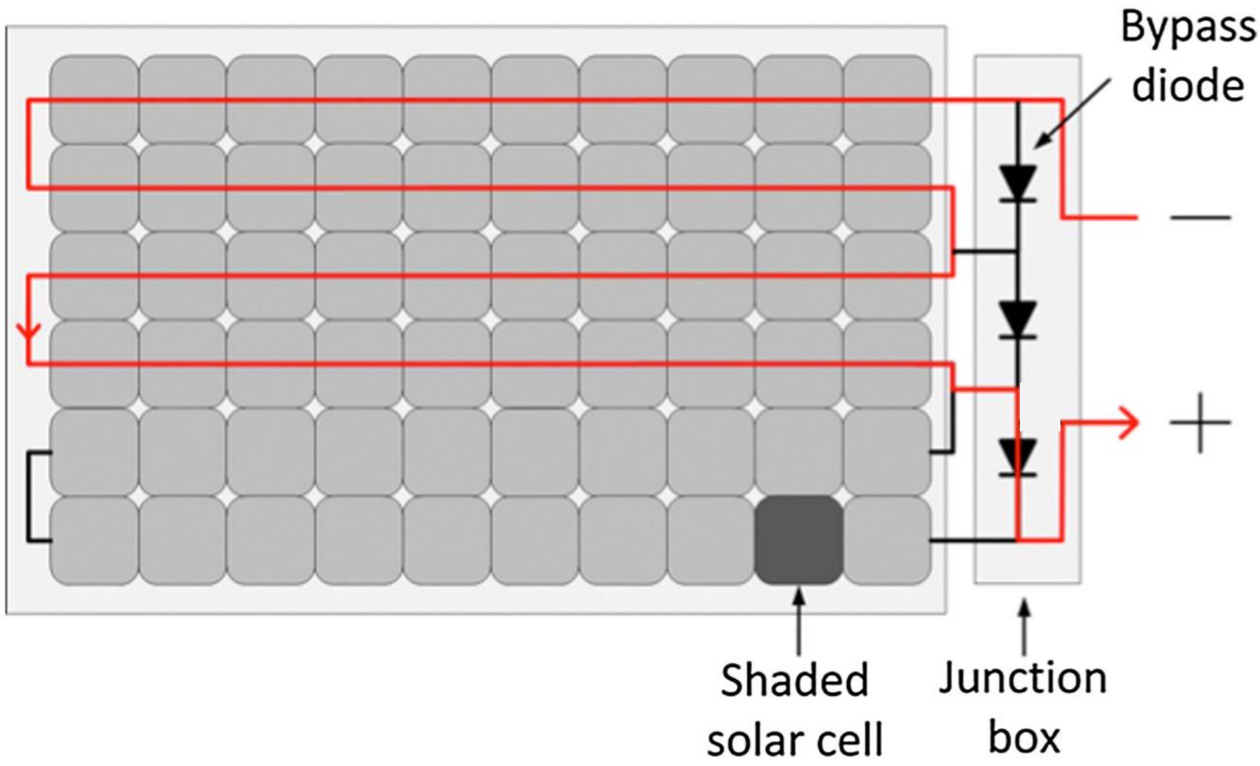
Reducing hot spot risk while increasing
maximum power in sub-optimal circumstances

Solar cells and bypass diodes- what you'll learn

- How bypass diodes are used in solar modules
- Effects of cell cracks, shading, soiling (all reduce Isc)
- Why would you use bypass diodes for solar cars or with SunPower cells
  - To account for current mismatch on one in-series string
- Why you *need* bypass diodes with front contact arrays and how often you must have them
  - To keep your array from catching fire in the case of cracked cells, partial shading, or bird poop
- A great reference for understanding solar cells: PV Education
  https://www.pveducation.org/pvcdrom/solar-cell-operation/iv-curve

Diodes Are Important for Power, Safety

- They allow current to keep flowing through unimpeded sections of the module in cases of in-series cells with imbalanced currents:
  - Shading
  - Bad cells
  - Angles of incidence
- Reduces hot spots, though not as big of a deal with SunPower cells
- 1 bypass diode/cell gives peak performance, but weighs and costs more, also is more complicated (reliability risk)



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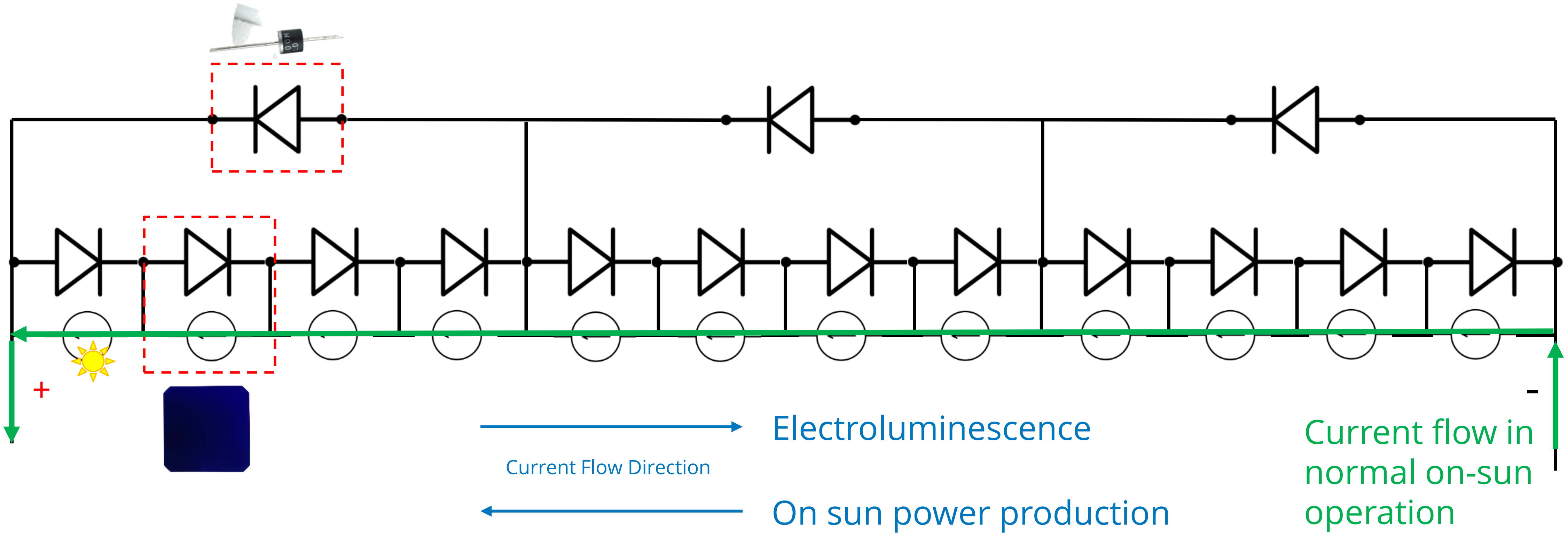
Solar modules are just a bunch of diodes



Example: This is a diagram that is pretty similar to the behavior of a 12 cell solar module that has 3 bypass diodes. Unless your geometry is *crazy* 3 bypass diodes is way too many for a 12-cell module.

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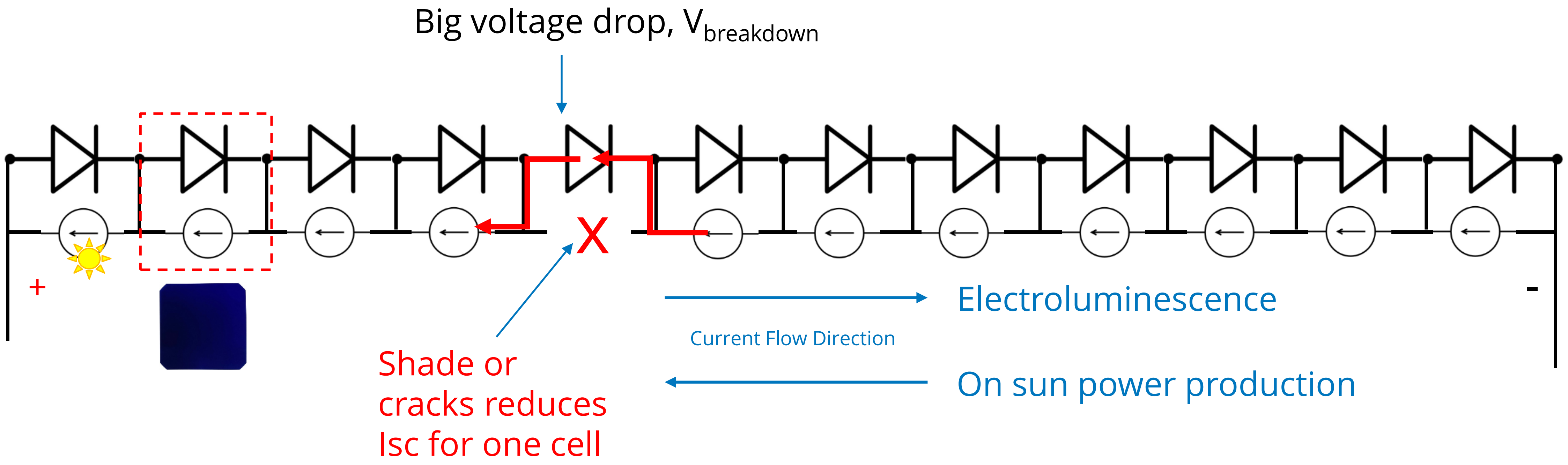
What if there were no bypass diodes?



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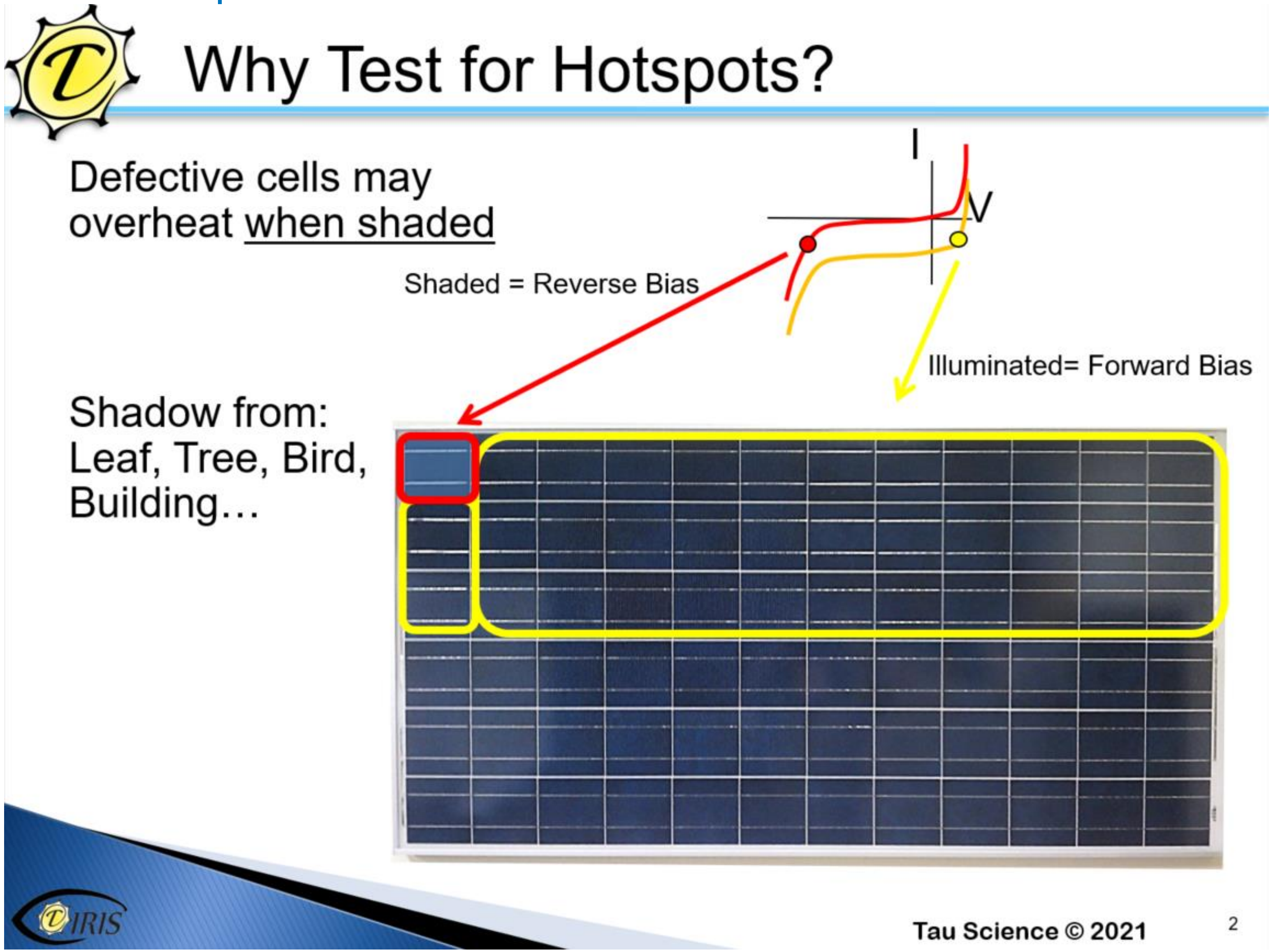
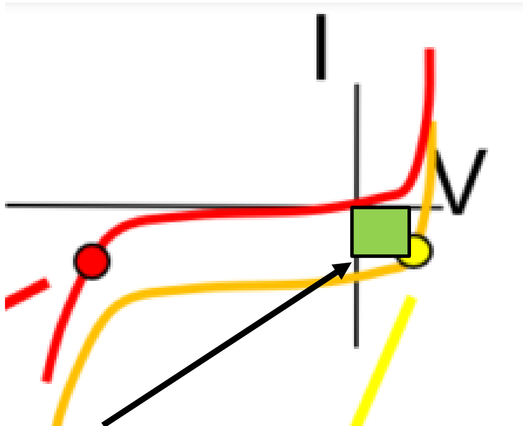
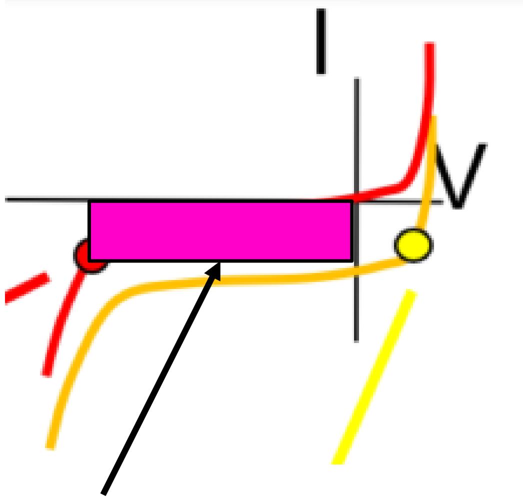
Hot Spots





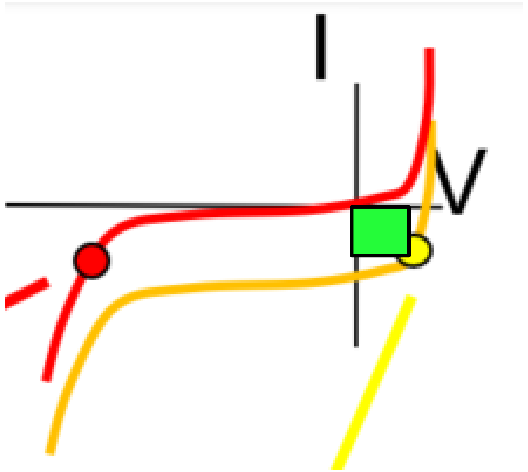
Box represents the energy produced by each non-shaded cell



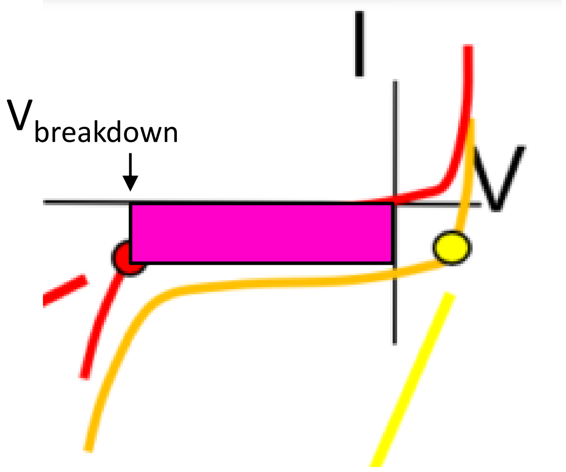
Box represents the energy dissipated by the shaded cell

Hot Spots: Risk in Front Contact Cell

- Front contact cells: Because the reverse bias breakdown voltage (Vr) is a much bigger number than the forward voltages, the power dissipated through a cell in reverse can be a huge amount of power. Example:
  - Vr = 25V
  - I = 5A
  - P = Vr*I = **125W dissipated over one cell**
  - You *must* have diodes often enough so each diode section covers fewer cells than the reverse breakdown voltage of your cells!
- SunPower Maxeon cells: The Vr is much lower (~6V), so power dissipated through a cell in reverse bias does not heat up very much. However, it still contributes to power loss equivalent to about 10 cells



Power produced by non-shaded cell



Power dissipated by shaded cell

Minimum number of diode calculation

- For SunPower Maxeon cells, each different angle on your car should have its own power tracker. If this isn't possible, you could use diodes on some areas of the array that are at strange angles.
- For front contact cells:
  - Measure your reverse bias breakdown voltage by hooking a single cell up to a power supply with the positive of the power supply hooked to the negative (normally the top side) of your cell and vice versa. Bias at a small current, such as 0.1A. Note the voltage. This is your reverse bias breakdown voltage, $V_{breakdown}$. Measure more than one cell to be sure. Measure it when the cell is warmer, too, if you can.
  - Measure the forward voltage of your cell: hook cell up to a multimeter and measure DC volts while the cell is in the sunlight.
  - Determine how many cells it would take in series to reach Vr. Put diodes more often than this number of cells.

$$N < V_{breakdown}/V_{oc}$$

(How to determine the maximum number of front contact cells per diode section)

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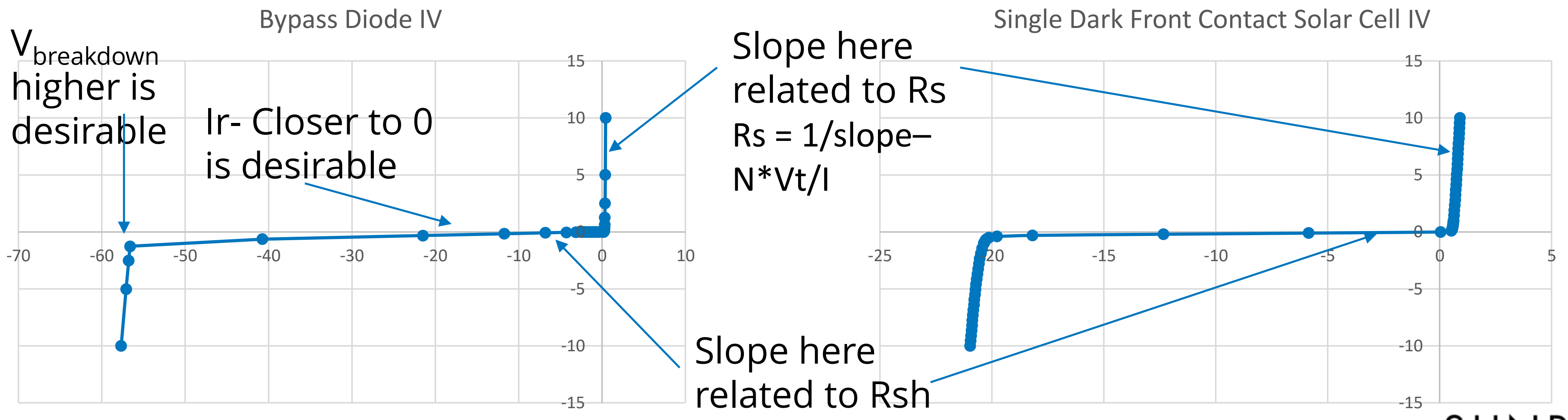
THANK YOU

Changing the way our world is powered

Diodes: Bypass Diodes and Dark Solar Cells

- Both "turn on" at around 0.5V in forward bias
- Both have higher voltage reverse bias breakdown voltages (-21V and -58V for cell and diode)
- You can add up these curves (voltage increase for diodes in series) or shift them up or down (illumination/cell size/parallel strings of cells) then add them together to make the IV curve of the whole module



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