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Solar Array Testing and Troubleshooting On a Budget

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Take-Away from Today

- Bypass diodes are recommended for all arrays, but *required* for front contact silicon
- Buy an **IR camera**.
- **Measure the performance** and quality of your solar array
- You can see cracked cells using **electroluminescence**
- **Your electronics will have problems** at some point; learn to detect shorts
- If your electrical connections are bad your car won't work well. **Intermittent connections** are the worst, but there are ways to find them.

Contents

- Introduction to Kat and SunPower
- What could go wrong with your array?
- Bypass diodes
- Testing and troubleshooting on a budget
  - Light IV curve tracing
  - Dark IV curve tracing
  - Electroluminescence
  - Thermal imaging
  - Open/short circuit detection

OSU Solar Vehicle Team 2014

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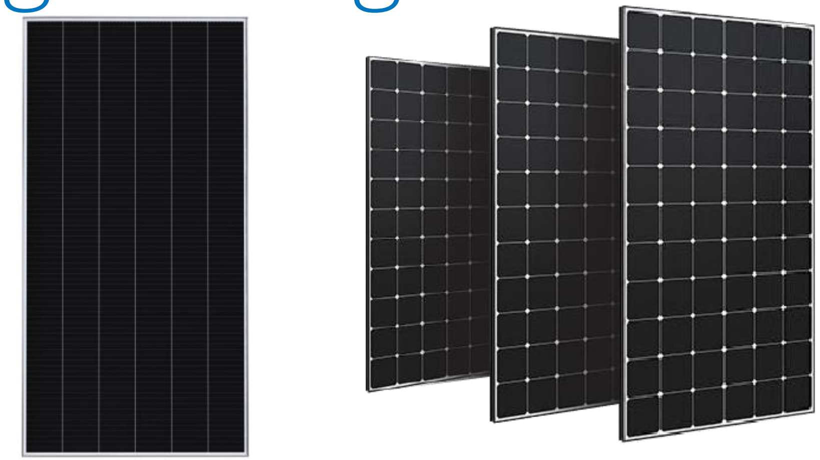
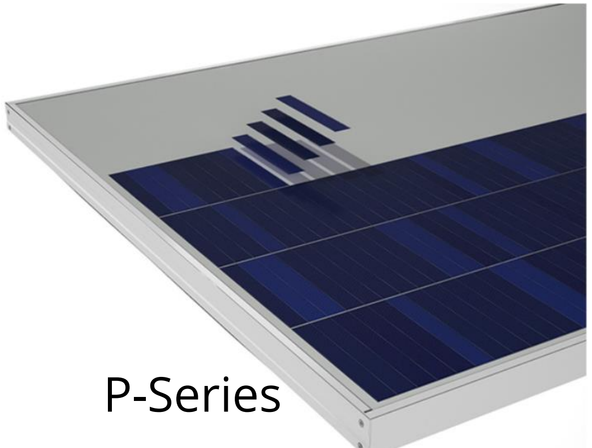
INTRODUCTION

My Role at SunPower: Reliability Engineering

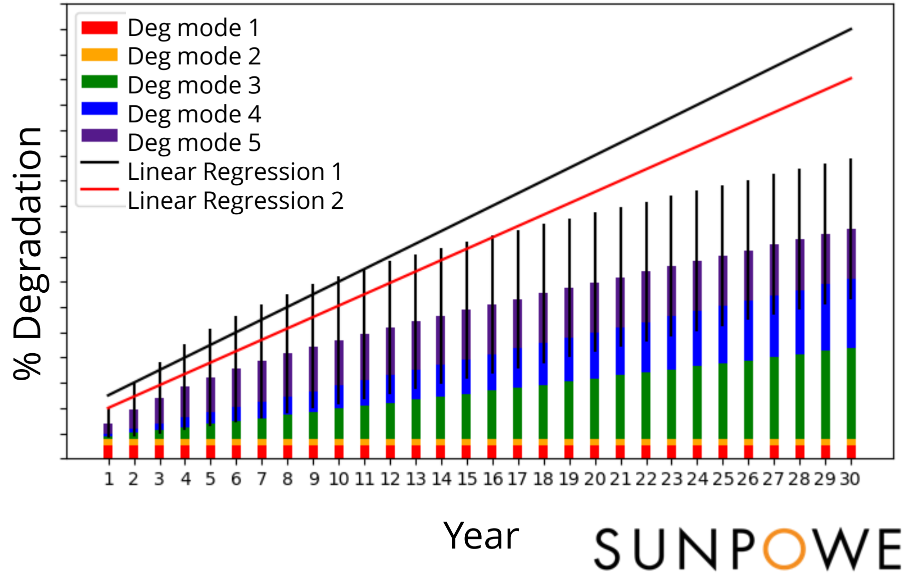
- Lead a team focused on proactive reliability of our P-Series Products (front contact shingled modules)
- Work with R+D to provide the best product to our customers, focused on safety, performance, and cosmetics (in that order)
- Calculate expected module degradation over warranty lifetime
- Balance academics with agility



P-Series X-Series A-Series



P-Series



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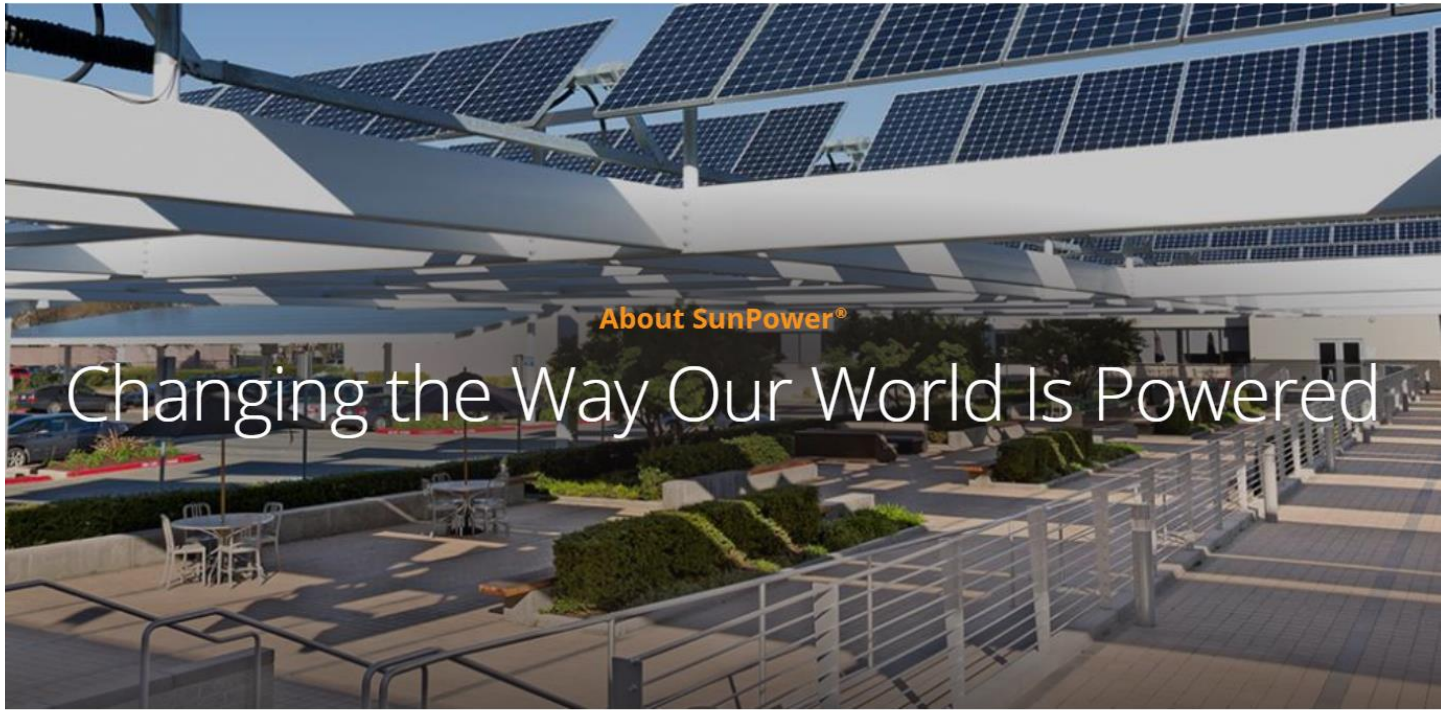
INTRODUCTION

About SunPower

- Headquartered in Silicon Valley since 1985
- Diversified portfolio leading residential, commercial and solar storage solutions
- Exclusive access to the world's highest efficiency solar panels featuring SunPower® Maxeon® cell technology
- Ranked #1 in U.S. Commercial Solar since 2017
- SunPower has received more than 700 patents for solar innovation



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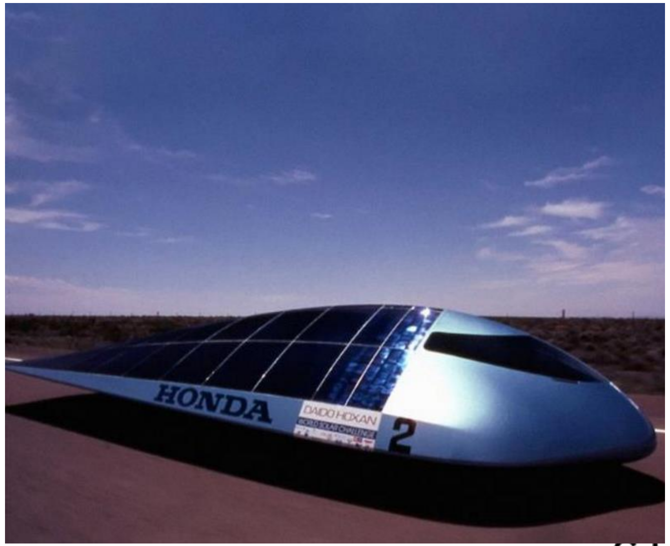
INTRODUCTION

SunPower - A History of Innovation

- Founded 1985 by a Stanford Professor
- High performance, high reliability
- All-back-contact cell developed
- NASA & Honda early customers
- Residential, commercial, and utility sectors



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INTRODUCTION

Solar Today – Stanford University

Saving ~**$420M &** offsetting 53% of electricity via **16** systems on campus and **68MW** offsite

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INTRODUCTION

Solar Array Requirements: Performance

- Safety first
- Output maximum power for minimum weight/aerodynamic losses
- Maintain power for the required life of the vehicle

Poor reliability is the #1 issue that will slow down your team

OSU Phoenix in 2013

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INTRODUCTION

Safety

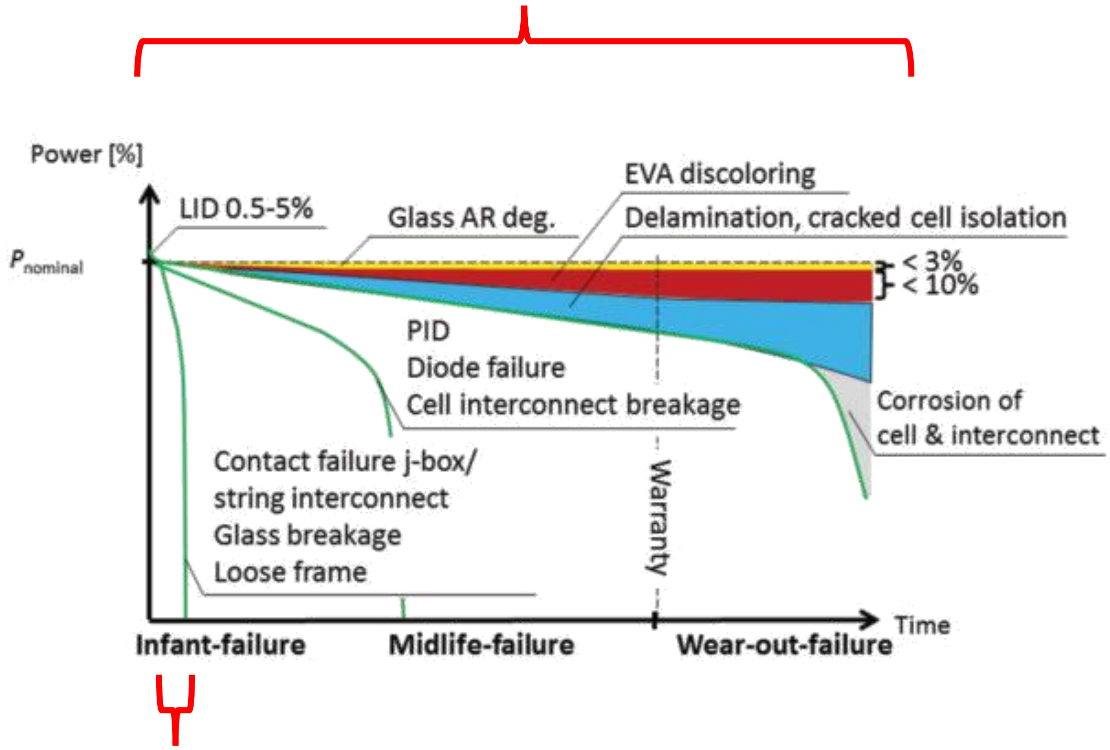
- Include safety in every plan
  - Personal Protective Equipment (PPE) (safety glasses, Arc Flash gear, HV gloves, etc.)
  - Refer to NFPA 70E Table 130.7(C)(15)(b) for PPE requirements according to the possible voltages and amperages you may encounter
  - Amps as low as 7mA can be deadly
  - Work in 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

INTRODUCTION

What could possibly go wrong?

- Cell **cracks**
- **Solder joint** failures
- Cell **current mismatch** or hot spots
- Insufficient **wire gauge** (hot wires!)
- **Light induced degradation** (0-5% dP in first 2 weeks, front contact B-doped cells)
- Laser cutting or soldering issues → **p/n junction shunts** junction (shunt resistance loss)
- Loss of **electrical isolation** (shorts to body/frame)
- **Soiling** (dirty array)
- Array **temperature too high** (loss of cell voltage 0.4%/°C)

Reliability concerns for traditional modules



Failure modes solar car teams worry about

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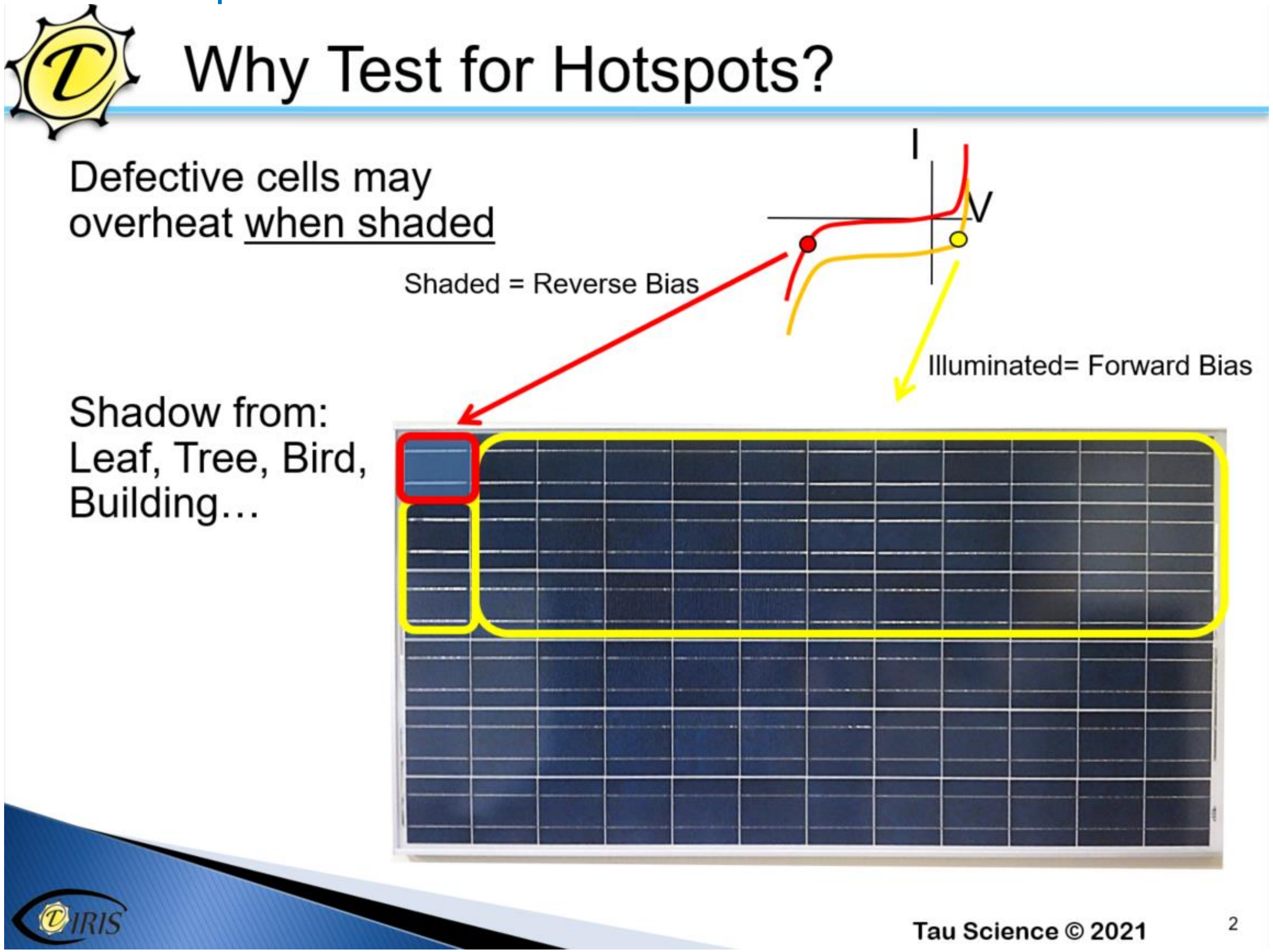
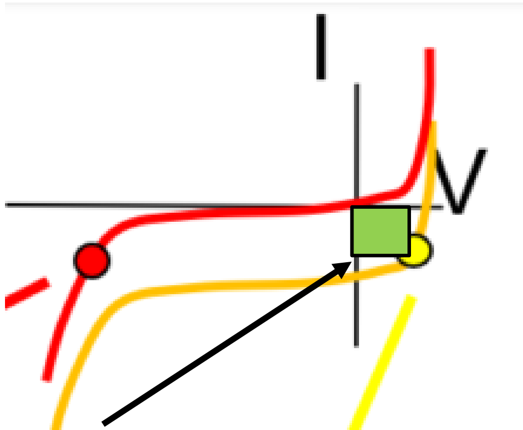
BYPASS DIODES

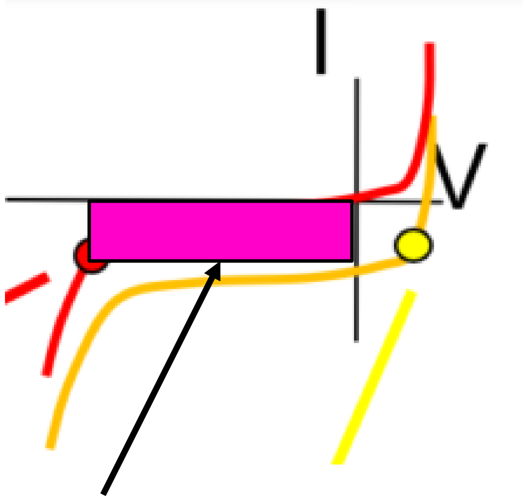
Reducing hot spot risk while increasing
maximum power in sub-optimal circumstances

Hot Spots





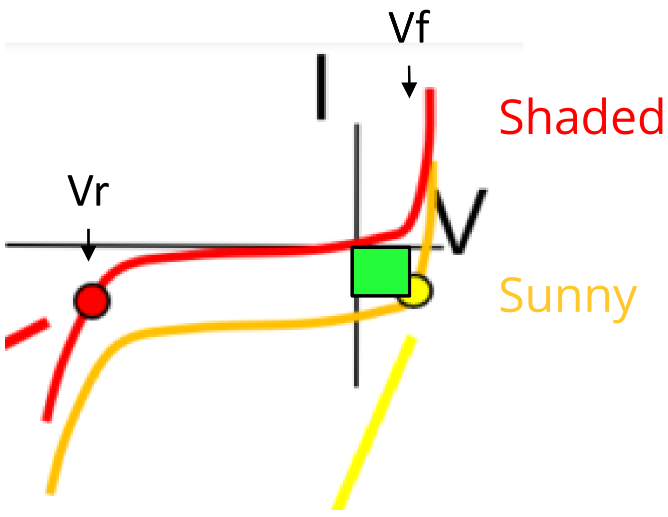
Box represents the energy produced by each non-shaded cell



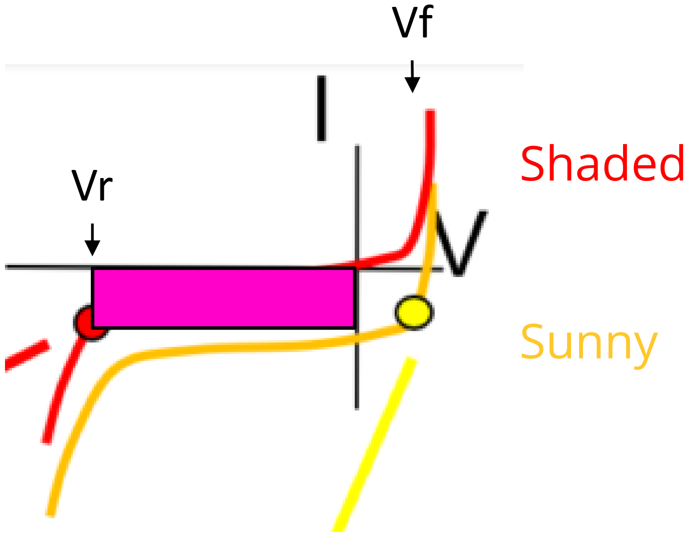
Box represents the energy dissipated by the shaded cell

Hot Spots: Risk in Front Contact Cell

- Front contact cells: Reverse bias breakdown voltage (Vr)>> forward voltage (Vf): dissipated power can be huge:
  - 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

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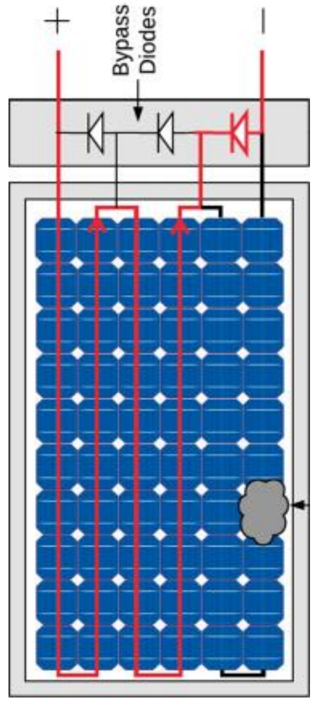
How to Calculate # of Cells Per Diode Section

- For SunPower Maxeon cells, have diodes separating cells that might get different insolation.
- For front contact cells:
  - Max cells on one diode: voltage must be lower than Vr
  - Measure your reverse bias breakdown voltage (Vr): reverse bias in the dark with a low current (0.1A) and measure voltage. Do this on several cells.
  - 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.



Source

$$N < Vr/Voc$$

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

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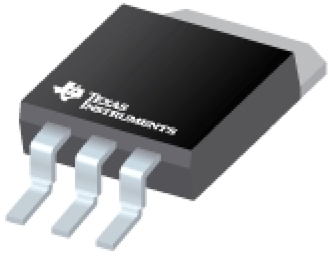
Ideal Bypass Diode



- https://www.ti.com/product/SM74611
- Regular bypass diodes cost 0.5V*I ~ 0.5*5 = 2.5W
- this ideal diode drops only 0.026V, only about 0.125W
- A great option for solar car- will stay cooler when diode is activated, can be laminated into the array

1 Features

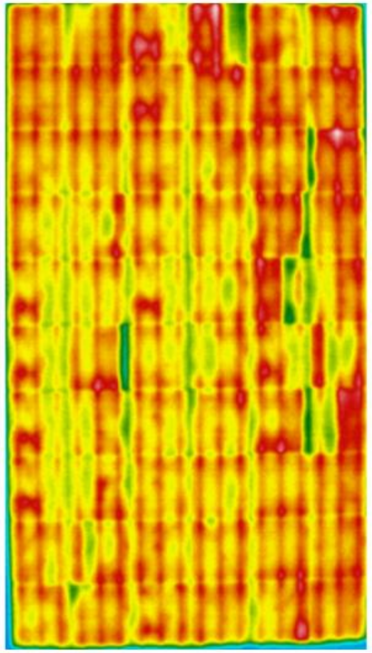
- Maximum Reverse Voltage (V_R) of 30 V
- Operating Forward Current (I_F) of up to 15 A
- Low Average Forward Voltage (26 mV at 8 A)
- Less Power Dissipation than Schottky Diode
- Lower Leakage Current than Schottky Diode
- Footprint and Pin-Compatible With Conventional D2PAK Schottky Diode
- Operating Range (T_J) of –40°C to 125°C

TESTING METHODS

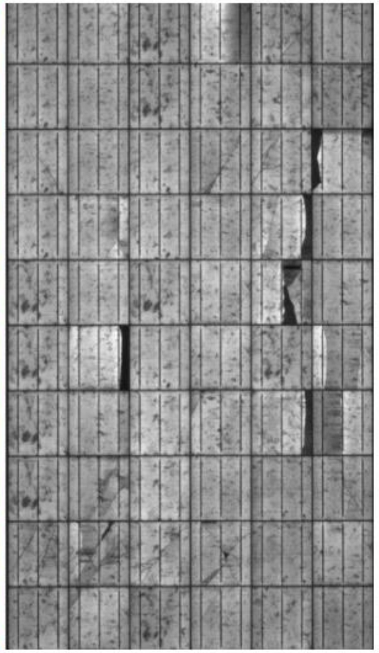
Methods and Equipment

- Power measurements – MPPT output or light IV curve tracing (Do you care how much power your array can make? Probably.)
- Cell health measurement – Electroluminescence (EL) images (Oooooo fancy!), Dark IV
- Wiring health measurement – Powered on IR imaging (GET AN IR CAMERA! They’re cheap.)

Visible Image



IR Image

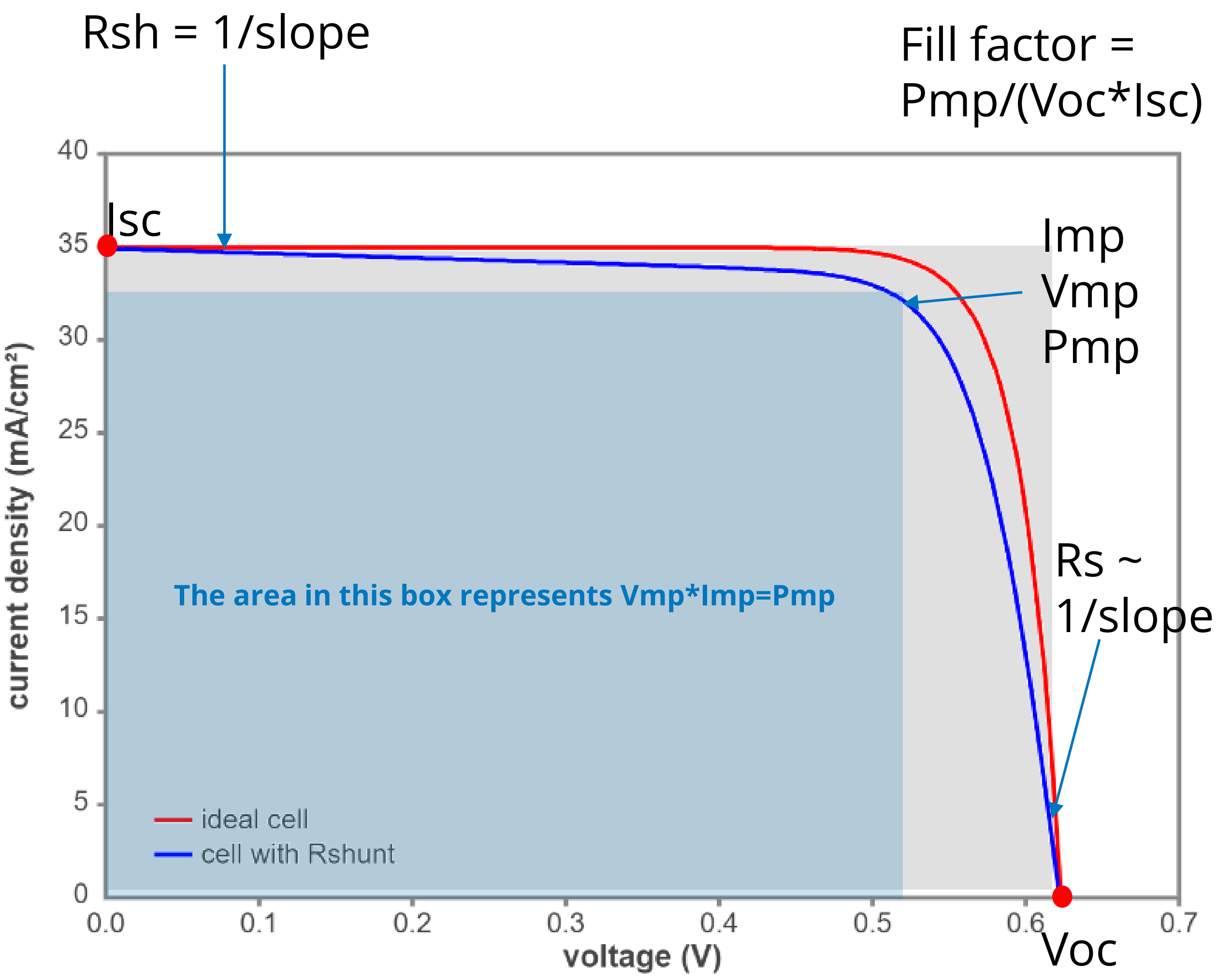


EL Image

https://www.et.aau.dk/laboratories/renewable-energy-conversion-storage/PV+diagnostic+imaging+laboratory/

Power Measurement

- Light IV "flash testing" is most common to determine power
  - 1 Sun light source
  - Source meter that can curve trace
  - Can be very expensive ($10k's - $100k's)
  - In a pinch you can make one with a source-meter, such as a Keithley 2461, and a halogen lamp, but it won't be as good as a flash tester
- In your solar car if your battery isn't full you can read MPPT output to determine max power (Pmp)



- Isc and Voc are the only points you can measure on this curve using a multimeter (in the sun)

https://www.pveducation.org/pvcdrom/solar-cell-operation/iv-curve

https://www.pveducation.org/pvcdrom/solar-cell-operation/impact-of-both-series-and-shunt-resistance

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TESTING

Finding Issues with Light IV Curves

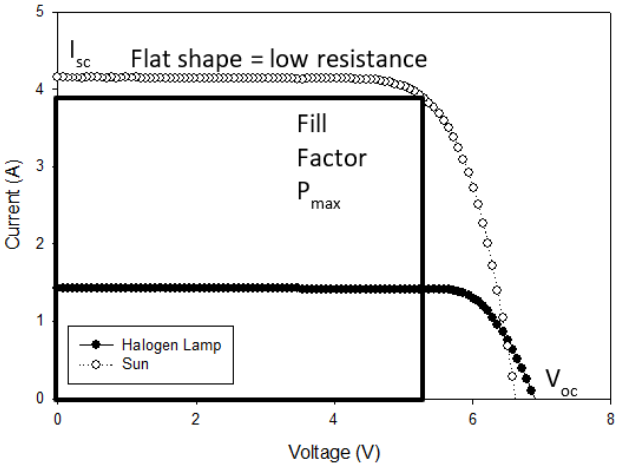


Figure 3: Representative IV curve for an entire solar module

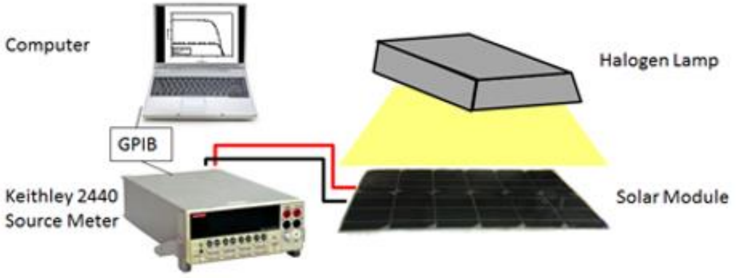
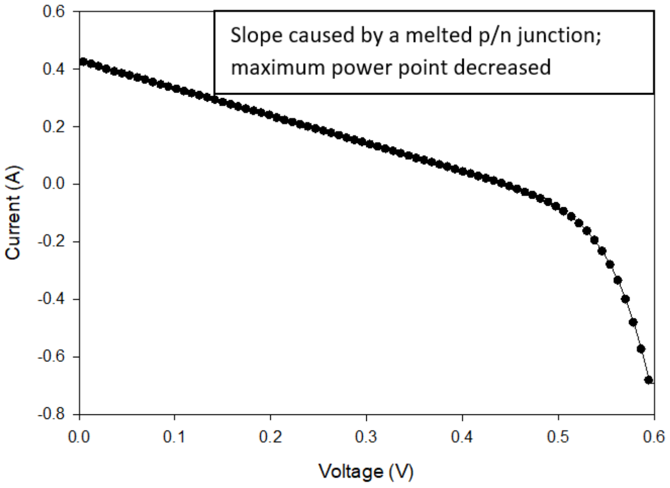


Figure 2: Experimental Set-up concept



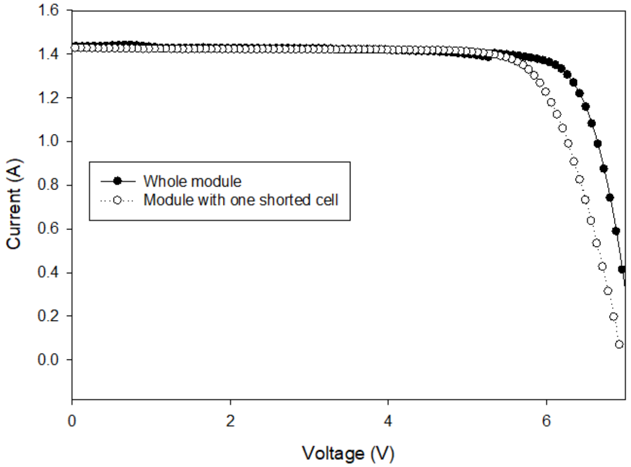
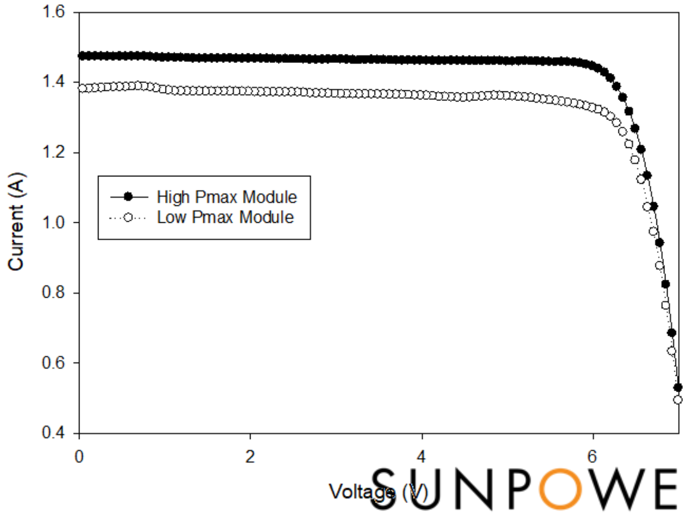


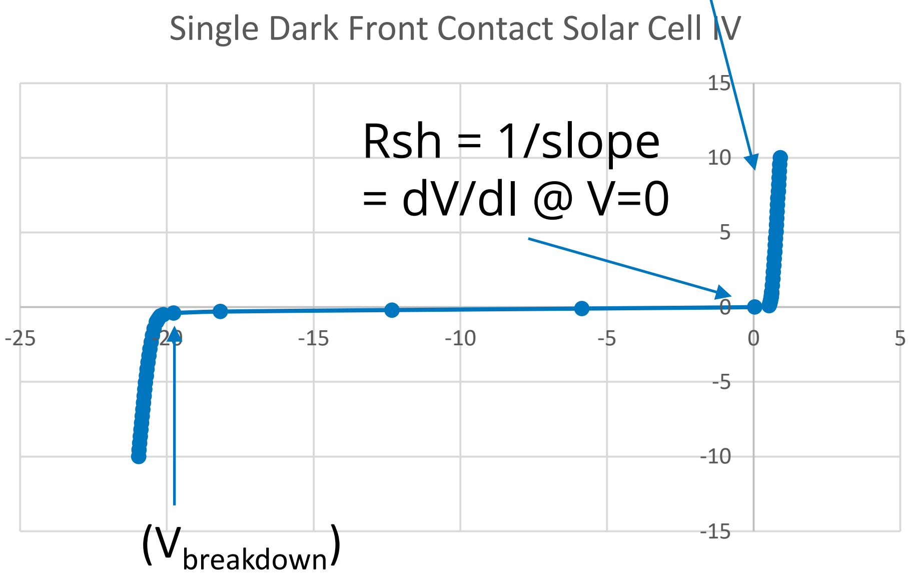
Figure 5: Shorting one cell in a string of twelve cells decreases the Voc and Vmax.



Dark IV Curve Tracing ($10k -> $100's)

- Can measure for series resistance (Rs), shunt resistance (Rsh), reverse bias breakdown (Vr)
  - Low Rsh indicates the p/n junction of the cell is being shorted by something conductive
  - High Rs means the metal parts of the cell or string are not sufficient or have some bad connections
- Cannot measure Voc, Isc
- OK to test soldering quality
- Can be done with just a power supply and a voltmeter (in the dark!) Program the power supply to source a range of currents and measure the voltage
  - Cannot measure Rsh if the cells have any light on them
  - Use pulsed supply or do measurement fast to reduce heating, otherwise will get different results at beginning and end of test. Measure low current first, or sweep both ways with a delay
- Can be done with just about any source meter, though a pulsed supply is best

$Rs = dV/dI – nV_t/I$
@ high I
$V_t = kT/q$



dV/dI = inverse slope of IV curve
Vt = threshold voltage = kT/q
I = current at which the slope is taken
n = number of cells in series
k = Boltzmann's constant
T = temperature in K
q = charge of an electron

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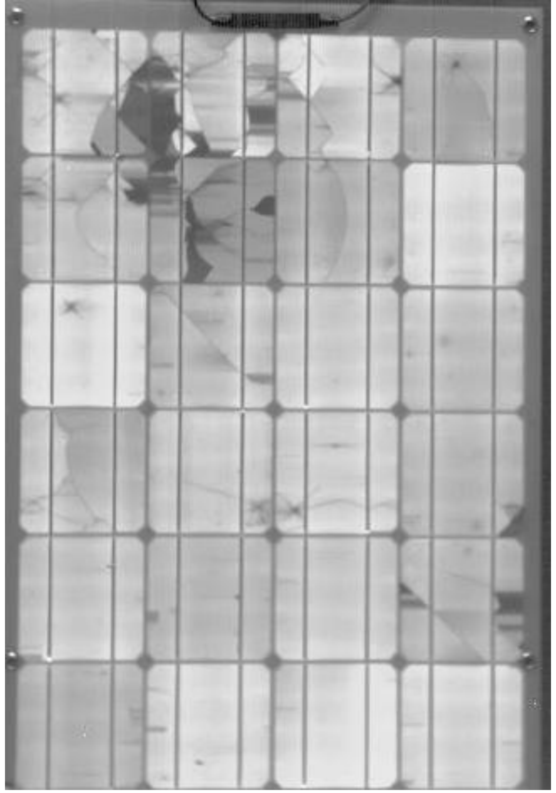
TESTING

Electroluminescence ($10k's -> $100's)

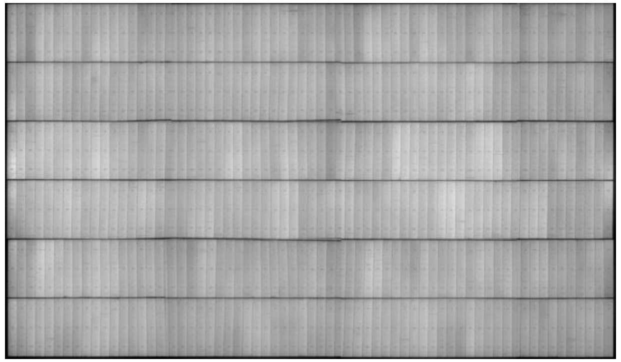
- Solar cells can work backward- if you put in current they will put out light
- When powered by a power supply, silicon solar cells emit light at ~1200 nm (near IR)
- For cells in series (same current) brighter areas have higher voltage
- Cracks are immediately visible as dark areas
- EL imaging is very sensitive, so you may see what looks like a lot of variation even if your cells are ok (example, very high power module below still has some intensity variation)
- EL cameras are very expensive! They have InGaAs detectors, usually. But you can make your own using an SLR digital camera with the IR filter removed, though you might need to take images in the dark

Electroluminescence of silicon solar cells using a consumer grade digital camera

M. Frazão [a], J.A. Silva [b,*], K. Lobato [b], J.M. Serra [b]



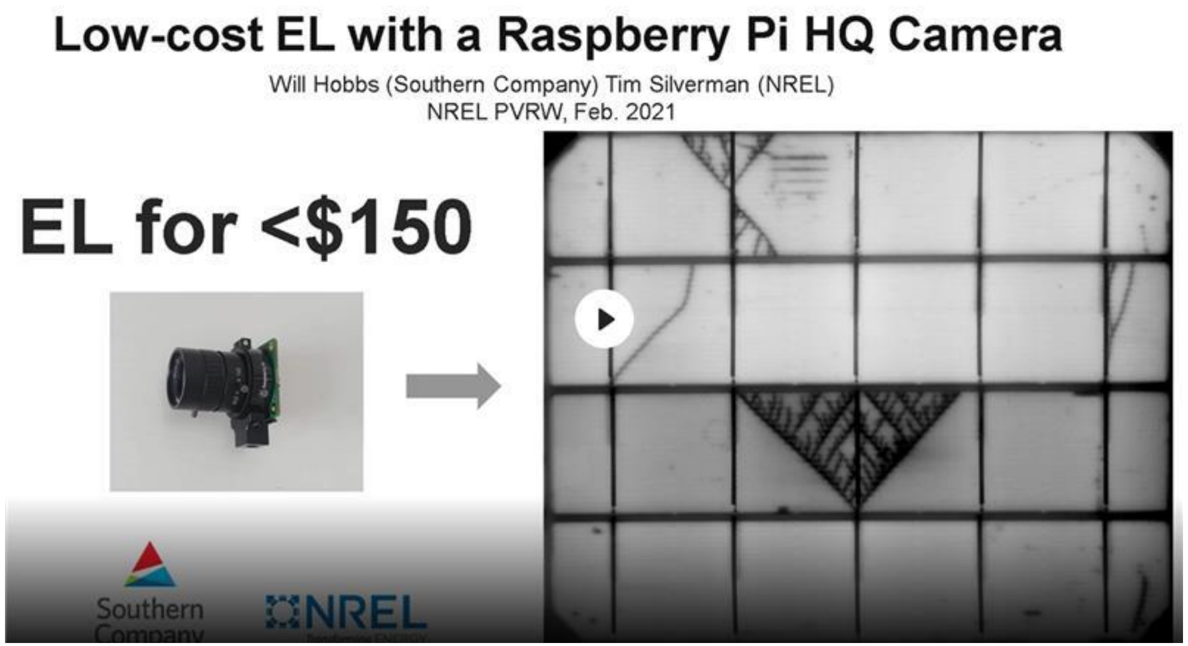
EL image of a flex panel purchased on Amazon

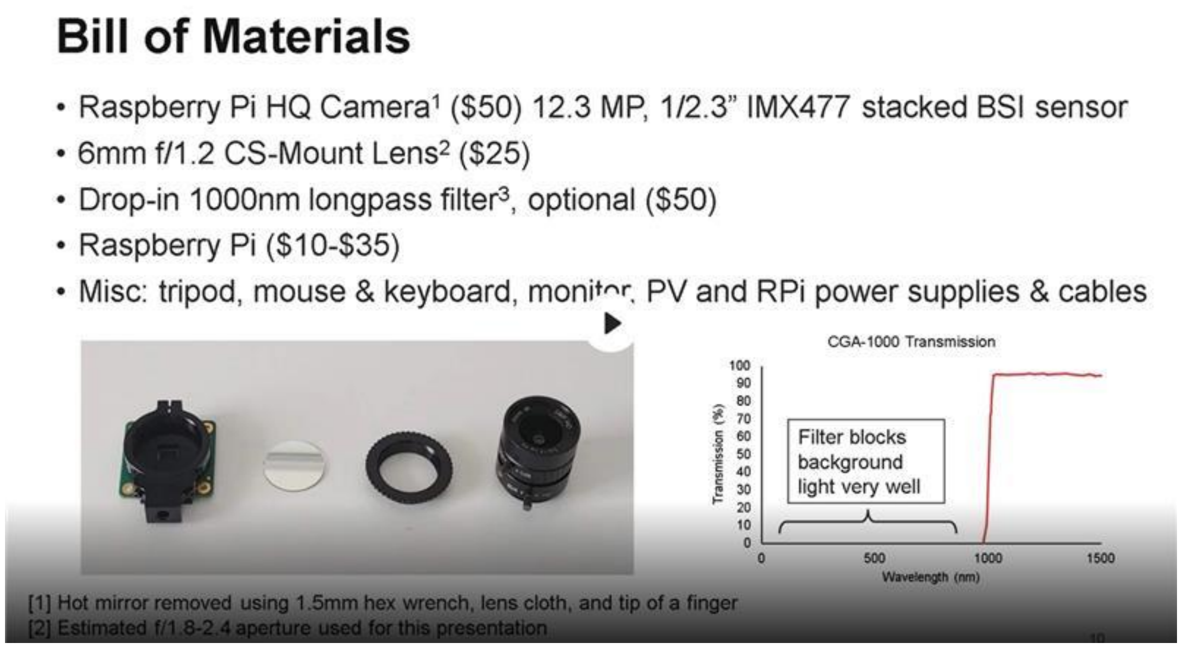


EL image of a SunPower P-Series panel SUNPOWER®

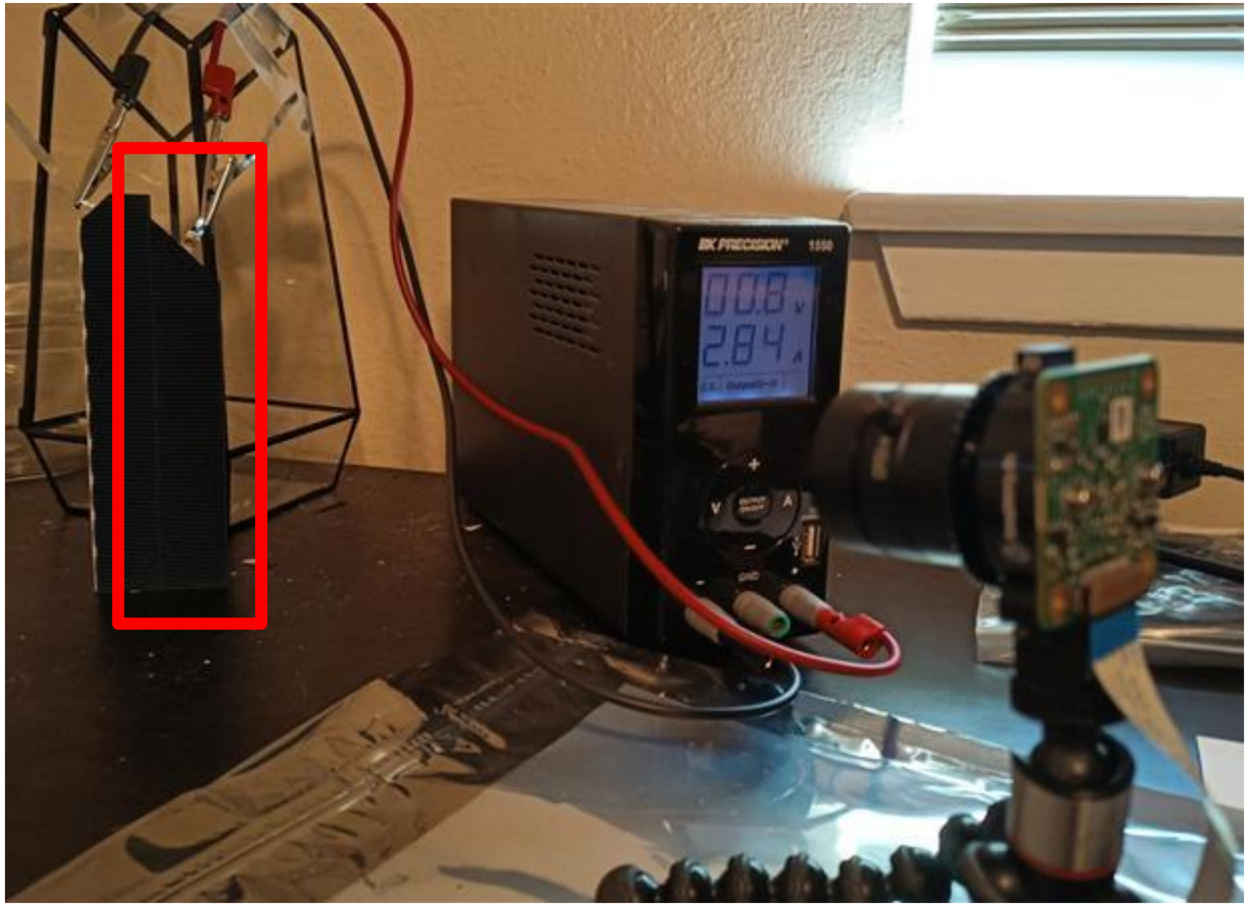
BONUS EL SLIDE

Electroluminescence with Raspberry Pi





Electroluminescence with Raspberry Pi: Reproduced



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Extra Information to Build Your Own EL Camera 1

- Camera: https://smile.amazon.com/gp/product/B08LHJR3K4/ref=ppx_yo_dt_b_asin_title_o02_s00?ie=UTF8&psc=1
- On lenses: the author used the "official" wide angle (6 mm) lens. Here are two sources:
- https://www.canakit.com/raspberry-pi-hq-camera-6mm-wide-angle-lens.html
- https://www.adafruit.com/product/4563
- 1000 nm longpass filter: https://www.newport.com/p/10CGA-1000
- On the back focus ring: if you loosen the back focus lock screw, you should be able to remove the back focus adjustment ring by gripping the wavy edge and turning CCW. Do note that the thickness of the filter prevents the back focus ring from being tightened back all the way, so this could impact the ability of some lenses to focus to infinity (the 6 mm lens focuses "beyond infinity", so it isn't an issue with that one). If this was a problem, you could remove some material from the back of the back focus ring (sandpaper and patience?).

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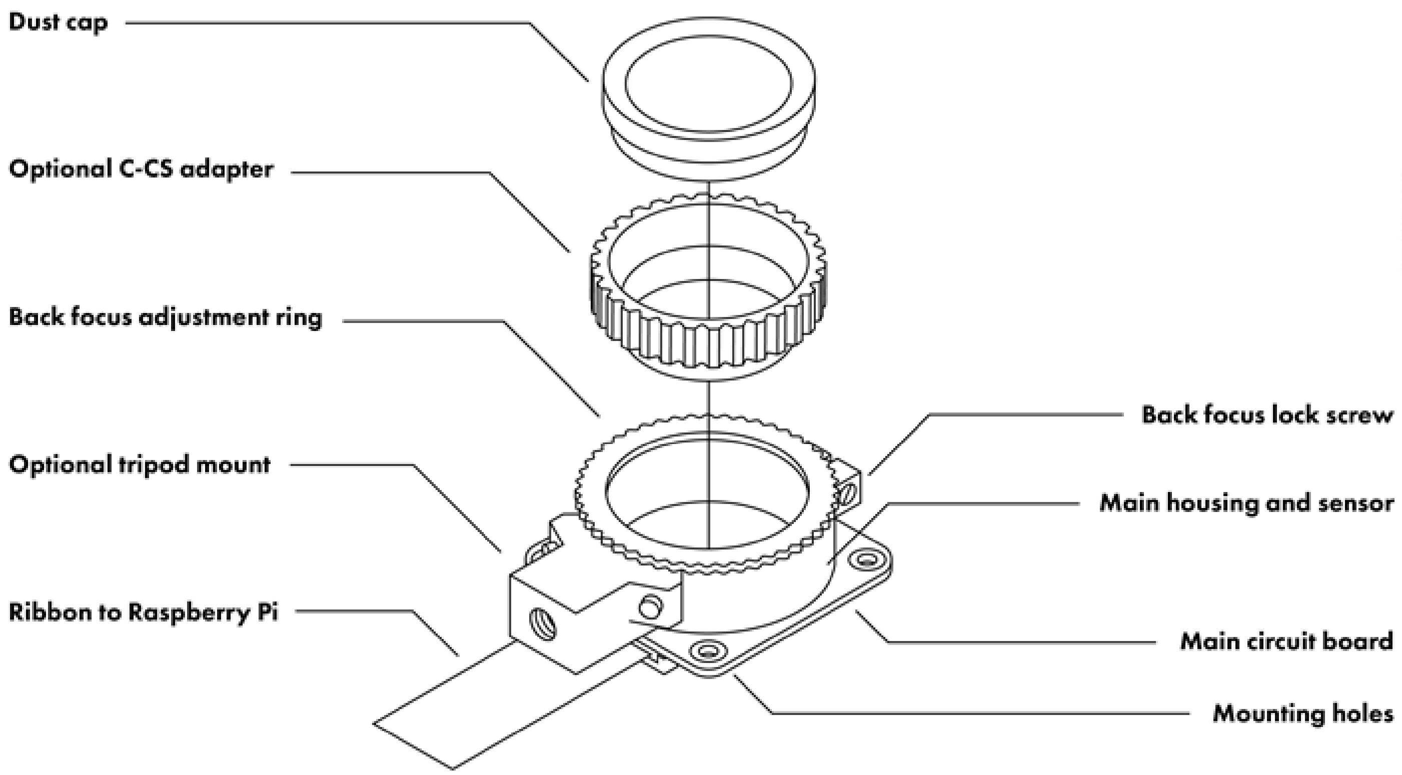
Extra Information to Build Your Own EL Camera 2



Get rid of blue IR filter here

Get rid of C-CS mount adapter here (keep larger, textured ring)

Extra Information to Build Your Own EL Camera 3

- On resolution/field of view: moving the camera about 2 m back from a full-size module should give you full coverage of the module (slide 5 approximates that).
- A few other tips that would have saved the author some time:
  - Make sure your raspberry pi is fully updated. I was using one that I setup a few years ago, and some of the raspistill features did not work at first. I think I had to run rpi-update (https://www.raspberrypi.org/documentation/raspbian/applications/rpi-update.md) to get it to work, although apparently this is a risky process.
  - The official camera guide is very helpful, although I think there are some features of raspistill that are not covered in it. https://magpi.raspberrypi.org/books/camera-guide/pdf/download
- My raspistill commands looked something like this:
  - raspistill -ag 1 -dg 1 -awb off -awbg 1,1 -ss 20000000 -n -md 0 -o EL_PVRW_renogy_1cell_6mm_stopped_20.0s.jpg
    - white balance (to get grayscale images instead of the common purple-ish tint):
      - -awb off: turns off auto white balance
      - -awbg 1,1: sets red and blue gain to 1
- Capturing raw images and then processing with PyDNG (https://github.com/schoolpost/PyDNG) or this updated version of dcraw, https://github.com/6by9/dcraw, could give better results, but I didn't test it out.

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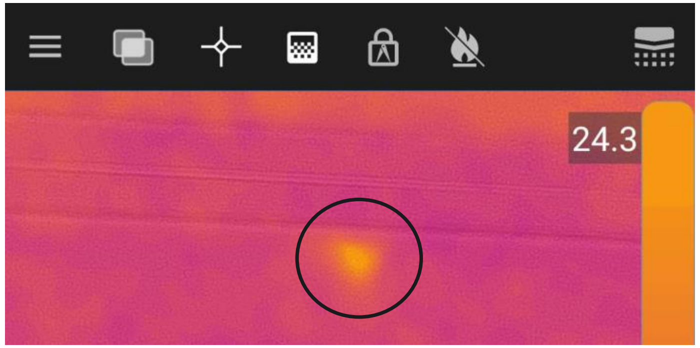
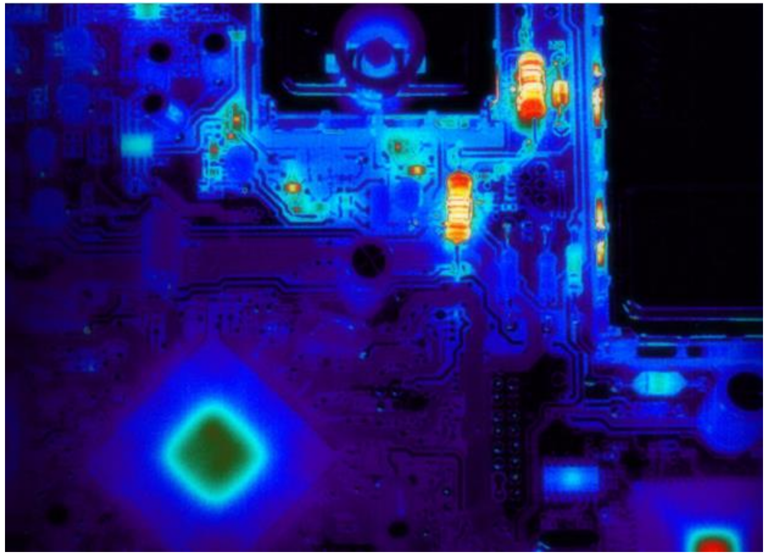
Thermal Imaging ($200)

- Inspect everything you make in IR
  - Watch in IR when you power up your PCBs or you MPPTs
  - Observe your solar array when it is in the sun using IR; you could detect hot cells or broken parallel pathways or other issues



A bad solder joint is clearly visible in the IR after a few seconds of turning on current flow through the area

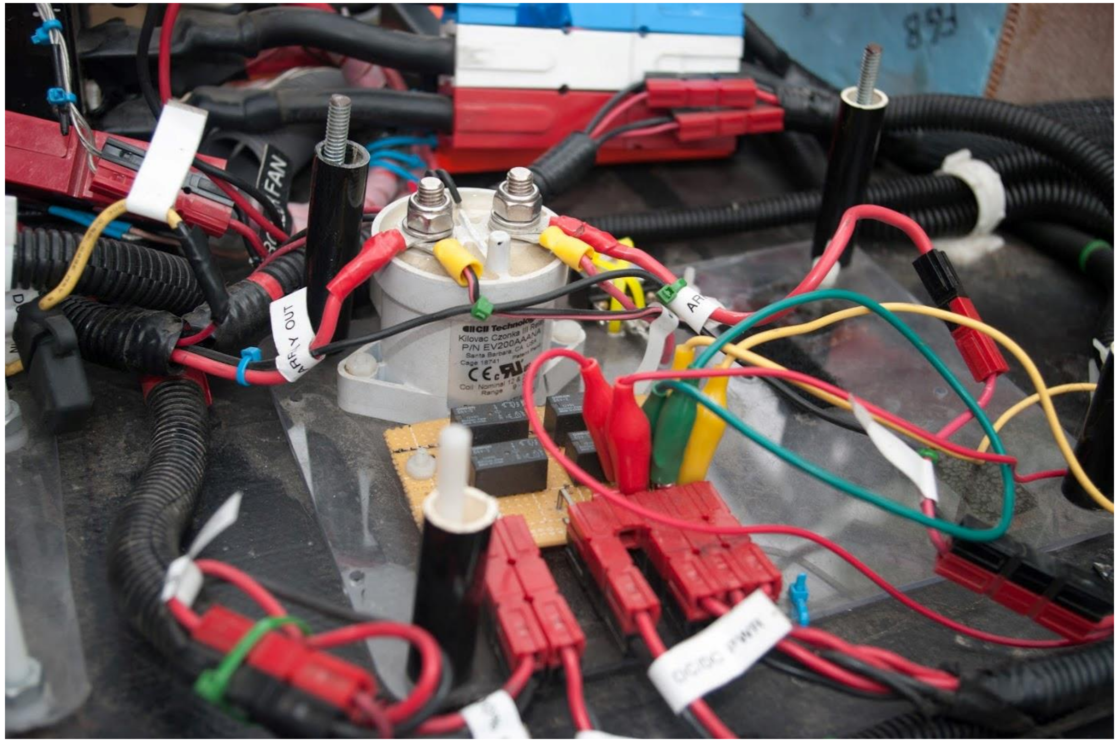


https://www.flir.com/instruments/science/electronics/

TROUBLESHOOTING WITH YOUR EARS AND EYES

Array and Electrical Problems

- So your electronics are all broken, now what?
- Most electrical problems come from intermittent open or short circuits.
- Bad connections and under spec'd wires – try to avoid this
- Use concepts from physic and basic electronics to solve your problems
  - I hope this saves you some time



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TROUBLESHOOTING

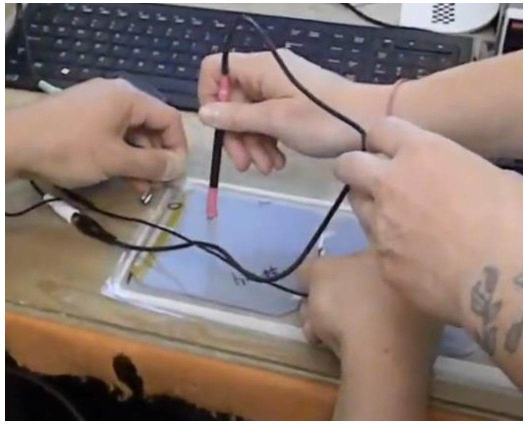
Short Circuit Detection

- Use inductively coupled AC signal injected into your circuit (or single solar cell) to find shorts
- Can inject a small signal into your circuit (single cell, PCB, wiring harness, entire car, etc.) and wave this wand around; you can hear it when the wand is near the short
- One time we found a short from the ground of the touchscreen in our carbon fiber steering wheel where the insulation has warn through and wires were touching carbon fiber, causing us to fail the electrical isolation test at scrutineering. One teammate used this tool to identify the location of the short, which could have been from any low voltage equipment.

For long wires and automotive wiring you can also use a Fox and Hound

<$100

https://www.shortsniffer.com/

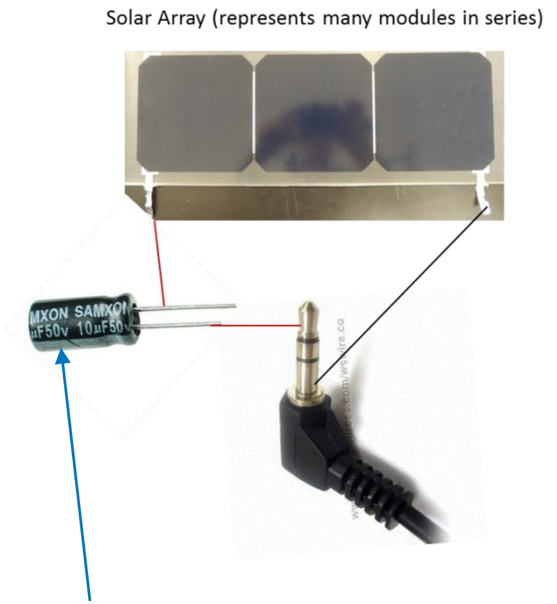


Using a ShortSniffer to find a piece of solder from careless soldering that is shorting the fingers on the backside of a SunPower IBC cell

TROUBLESHOOTING

Intermittent Connection Detection

- Intermittent connections are the worst
- You can find some types of intermittent connections using an audio technique
  - Hook your circuit (such as a solar array) up to speakers that have auxiliary power
  - Put a 10 uF (approximate, make sure it's rated for your array's voltage) capacitor in series with the solar array and the audio jack of the speakers
  - Turn on the power to the speakers and turn the volume up until you hear some fuzz. Disconnect and connect one part of the circuit and make sure you hear static.
  - Tap gently on the different joints that could be intermittent; once the circuit goes in and out of connection you'll hear the noise



Wrong voltage rating 😮

Technique courtesy of Carl VanWormer

Power-On Surveys with Infrared Imaging

- When you power up your solar array or a PCB or anything on your car, have someone watching with an IR camera
- Notice anything that gets hot- if it is hot that means it has current going through it. Normally this is fine
- If anything is getting much hotter much faster than the stuff around it power back down and check your circuit. Don't touch the hot stuff.
- You will detect under spec'd wires, high power short circuits, backward diodes, and other issues this way
- If an area is cold when it should be hot that means current isn't getting to it
- Power loss is $P = I^2R$, so for parallel pathways the hot spots are the low resistance areas, for series pathways the hot spots are high resistance

IR modules that use your cell phone as a screen are ~ $200

Insufficient Wire Gauge

- Did you use the wrong wire or connector?
  - Use the right connections – solder is good, wire nuts are usually not great for vehicles
  - Anderson power pole connectors work well in vehicle applications
  - Ask other solar car teams what connectors have worked well for them *for an entire race or longer*
  - Use the right crimping tool
  - Choose the right size connectors for your wire gauge (as determined by intended current)
- Know the currents you will have in which wires and spec them for those currents. Include fuses at the appropriate ratings (AC/DC, current, voltage)!
- Rule of thumb: 30g Cu wire melts at 10A
- Use stranded wire

Wire Size	Area mm2	COPPER	
AWG		VDI	Ampacity
16	1.31	1	10
14	2.08	2	15
12	3.31	3	20
10	5.26	5	30
8	8.37	8	55
6	13.3	12	75
4	21.1	20	95
2	33.6	31	130
0	53.5	49	170

https://www.altestore.com/howto/wire-sizing-tool-for-12-24-and-48-volt-dc-systems-a106/

Anderson Powerpole 30A Connectors

GOOD LUCK!

BONUS SLIDE

One more thing…

Watt (W): unit of power- a rate of energy transfer

THIS CAR

Uses 1000 watts of power to drive 45 mph

After an hour of driving, the car has used 1,000 Whr of energy.

If the team forgot to plug in the solar array, they would have exhausted ¼ of the 4 kWhr battery pack

(Unfortunately this happened once)

Watt-hour (Whr): unit of energy

THIS BATTERY

Holds energy in Whr

After an hour of discharging at 1W of power it will have lost 1 Whr of energy

SUNPOWER®

THANK YOU

Changing the way our world is powered