The Basic Principles of FOZHS (Forward-Only, Zero Hot-Spot) Technology

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The link between destructive levels of solar cell self heating and the application of large reverse bias voltages to solar cells is discussed. The mathematics of a method to restrict solar cell operation Forward Only resulting in Zero Hot Spots is disclosed, proven and experimentally demonstrated. Defect free solar cell temperatures in a properly designed solar module may exceed the thermal limits of encapsulates used within the module. The mechanism for this mode of self heating in defect free solar cells is identified and described mathematically. Types of defects which significantly enhance self heating are identified.

1. In reverse-bias conditions, cell defects can incite uncontained, catastrophic failure.
2. Defect-free cells can and will develop defects in the field.
3. If cell operation is restricted to forward-bias only, the defects are of no concern.

Definitions

Un-contained catastrophic cell failure: A failure within the cell that results in dangerous conditions outside of the solar panel envelope. These conditions include, but are not limited to, combustion of the envelope, escape of molten metal or semiconductor materials, and exposure of potentially lethal voltages.

Cell defects: Include, but are not limited to: micro-crack, junction breakdown, hot electron enhancement, linear shunts (ohmic), and non-linear shunts (avalanche).

Mathematical Examination of Forward- vs. Reverse-Voltage Modes

1. There is not sufficient energy available under forward bias to cause an un-contained catastrophic cell failure.

   The maximum power available to drive a defect in a forward-biased cell is V_F (cell forward voltage) x I_{SC} (cell short-circuit current), which in large cells (156x156mm) can approach 0.6V x 10A, or 6W. The same cell routinely dissipates 24W of solar input, so 6W is small by comparison. In most cases, the 6W is simply a component of the 24W.

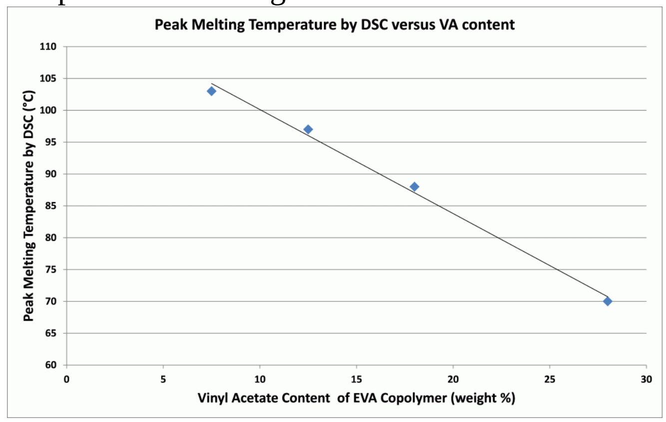
   The only way 6W of electrical power could cause any cell damage would be if the current were concentrated in a very small area. But under forward-bias conditions, the e-field in the cell (0.6V) is too weak to force charge carriers to concentrate. In solid-state physics terms: The diffusion component (the tendency for like charge carriers to repel one another and diffuse) is greater than the drift component (electric potential that imposes a net movement of the charge carriers).

2. Under reverse bias, there is much more power available to drive a defect. The maximum power is V_R (sub-string reverse voltage) x I_{SC} (short-circuit current). V_R is routinely -12V when the sub-string bypass diode is intact, and can be as high as -25V in the event of a bypass diode open-circuit. Either of these voltages is enough to force current to concentrate in a defect area, due to its lower shunt resistance.

   Even in a defect-free cell, the imposed reverse-bias causes severe heating. A 10%-shaded 10A cell will produce 9A or so in full sun, but if the inverter draws more than that from the string, the bypass diode will be forward-biased, effectively shorting out the substring. The other, fully-lit, cells in the substring will cause the 9A of photo-current to flow *backwards* through the cell at -12V. Now the electrical dissipation is 108W, instead of only 6W. Solar insolation is 90% of 24W, or 21.6W, for a total of about 130W.

For reference, a 156mm x 156mm cell absorbs and dissipates at most 24W of solar energy with a typical thermal rise of 25°C (NOCT = 45°) or about 1°C/W. In a 10%-shaded cell, the reverse-current flow will be mainly in the lit area, because that's where the charge carriers are. The insolation will also be limited mainly to the lit area. Since the 130W will be dissipated over 90% of the cell area, the expected temperature rise is 1/0.9 = 1.11°C per watt. 130W will create a 144°C temperature rise in the lit area. The cell will be subjected to additional thermal stress due to the temperature gradient between the lit and unlit areas. In a 50°C environment, the cell temperature will approach 200°C.

The chart below illustrates the thermal limitations of EVA. The most rugged formulations start to melt at 105°C. Beyond 200°C (not shown) EVA devolves into components including acetic acid.



Again, the above example is for whole-cell heating, typically caused by partial shade, and pre-supposes a defect-free cell. However, many cell defects exist on a microscopic scale and, because of the higher (imposed) cell voltage, result in very high local power densities. A defect occupying 5% or less of the cell area may create temperatures exceeding the melting point of silicon (1,414°C). Typical micro-crack widths are in the 2µm range; far smaller than 5% of the cell area.

3. Zener, avalanche, and other breakdown modes occur only under reverse-bias conditions, so maintaining forward-only bias eliminates them as failure modes.

Principle of Maintaining Forward-Only Bias by Monitoring Panel Conductance

Given:

1. The Maximum Power Transfer Theorem: Match R_{LOAD} to R_{SOURCE} for maximum power transfer to the load.
2. The Property of Equality of Exponential Functions (-1 in this case, inverse): Matching G_{LOAD} to G_{SOURCE} will also transfer maximum power, where G = 1/R = conductance.
3. The Definition of I_{SC} is the conversion of a constant photon flux to a constant current flow of a PV cell at zero volts characteristic, and I_{SC} is constant for small changes in V. In other words, as V across the cell approaches 0, the cell approximates an ideal current source, which by definition has a conductance of 0 (i.e., an impedance of infinity).
4. The summation of the Series Conductance Equation. ($1/G_{TOTAL} = 1/G_1 + 1/G_2 \ldots$)

Assertions:

1. The maximum power transferred will be when the small signal impedance of the generator matches the large signal impedance of the load by [1].
2. The maximum power is also transferred when the small signal conductance of the generator matches the large signal conductance of the load by [2].
3. As the voltage across a PV cell approaches zero, its conductance approaches zero by [3].
4. For any number of PV cells in series, the conductance of the entire string of PV cells approaches zero if the voltage across any individual cell approaches zero by [4]. ($1/G_{CELL}$ approaches 1/zero approaches infinity, therefore $1/G_{TOTAL}$ also approaches infinity; i.e., G_{TOTAL} approaches zero.)

Therefore:

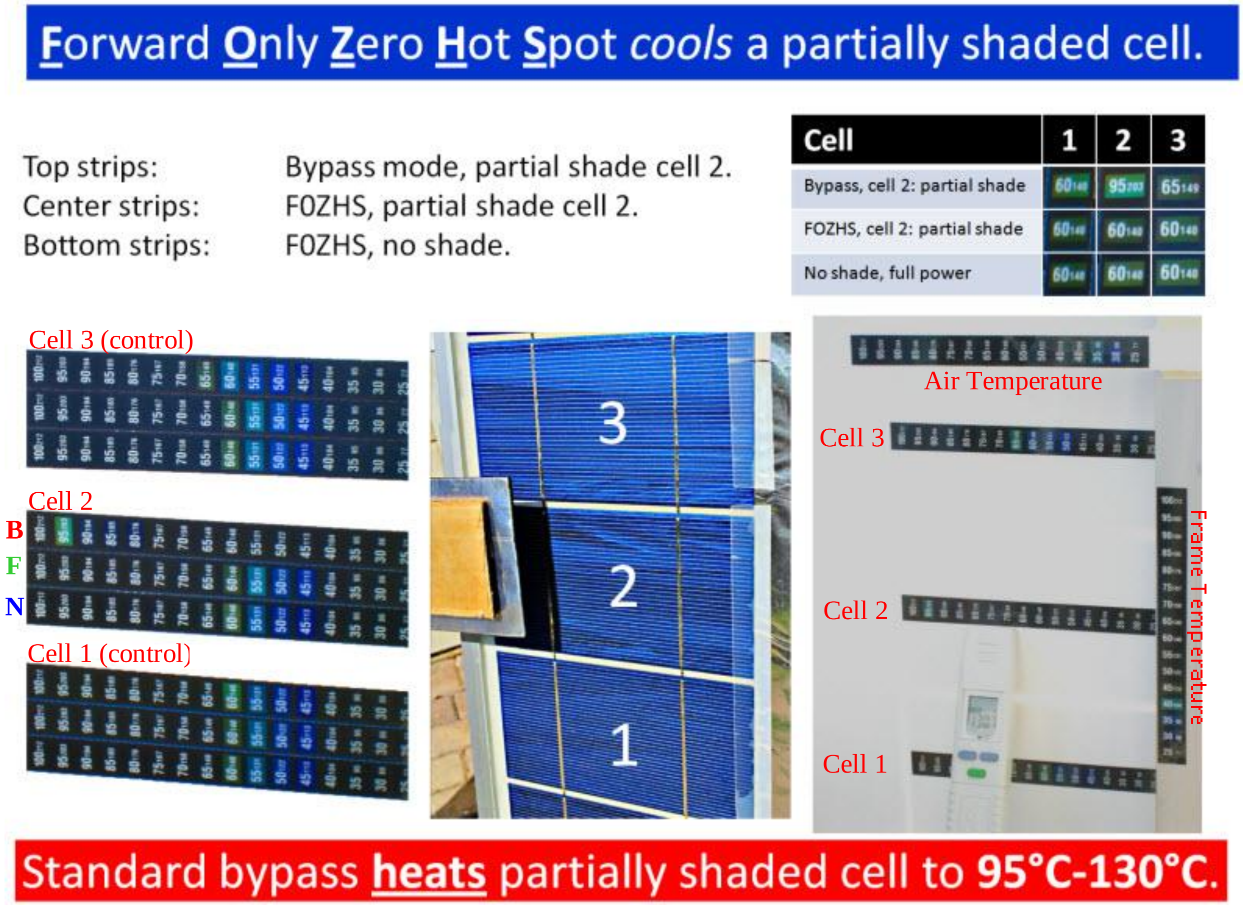
A. For small signal conductance greater than zero, every individual cell must have a voltage greater than zero across it.
B. For large signal conductance greater than zero and small signal conductance made equal to the large signal conductance, the maximum power available is transferred without the possibility of reverse biasing any PV cell.

The idealPV FOZHS algorithm measures the panel conductance much more rapidly than any natural phenomenon can slew it. At the first sign of an encroaching shadow on any cell, the FOZHS system compensates to keep the shaded cell (as well as all other cells in the string) forward-biased at all times.

References and Definitions in the above analysis

http://idealpv.com/ESW/Files/Proof_for_Forward_Only_Zero_Hot_Spot_120801.pdf

Experimental Example



Images of Forward-Only Zero Hotspot Technology

The measurement strips are Telatemp 438-3 Reversible LCD Labels: 25-100ºC.
The strips highlight their numbers with different colors to indicate temperature:

Tan means the temperature is *lower* than the number;
Green means the temperature is *equal* to the number;
Blue means the temperature is *higher* than the number.

Intermediate temperatures may be interpolated from the hues of adjacent numbers.

The raw data presented above indicates an average temperature across the cells as follows:

Cell:	1 (control)	2 (test)	3 (control)
Bypass mode, cell 2: partial shade	60ºC	95ºC	64ºC
FOZHS cell 2: partial shade	58ºC	58ºC	59ºC
No shade on any cell, full power	58ºC	59ºC	59ºC

The experimental setup is shown in the lower-right corner of the Figure. The measurement devices are, counterclockwise from top:

Top: Air temperature = 35ºC (Temperature strip thermally isolated with Styrofoam)
Cell 3 backskin temperature = 64ºC
Cell 2 (partially shaded) backskin temperature = 95ºC at strip location
Cell 2 (same conditions) backskin has 130ºC hot-spot (measured with narrow-field pyrometer)
See close-up of the pyrometer, below:

Bottom: Cell 1 backskin temperature = 60ºC
Along the right-hand edge: Frame temperature = 40ºC

Since all of our cell-temperature measurements were at the backskin, we know the cells themselves were hotter, but we don't know exactly how much hotter they were. Basic thermodynamics tells us, however, that a higher external reading means a higher thermal gradient between the cell and the backskin. To calculate the internal cell temperatures based on backskin readings would require an accurate thermal model of the panel, which we do not have available. However, the data we do have shows that a great deal of heat is being dissipated in the shaded cell. The 130ºC reading is a 95ºC temperature rise above ambient, measured on the far side of an insulating plastic backskin layer.

Another point of interest is how much temperature variation there was across the shaded cell. Under the LCD temperature strip, it was 95ºC, but scanning with the narrow-field pyrometer showed temperatures on the lit area to vary from about 90ºC (not shown) to a high of over 130ºC (shown). Meanwhile, in the shaded area, the cell was only about 50ºC (not shown). Since silicon is highly thermally conductive (almost as good as aluminum) there is a common misconception that large thermal gradients across a silicon cell are not possible. However, since the cell is very thin (between 120 and 200µm), horizontal thermal conductivity is relatively poor. Hot spots can and do occur, as shown by the experimental data.

Another point of interest is that the cell under test had no visible signs of damage. Even so, reverse-biasing caused localized hot-spots in addition to the overall temperature rise. This is a clear sign of reverse currents concentrating (and heating) areas of lower shunt resistance within the cell, even though the cell showed no signs of being cracked (e.g., intense heat build-up in a very small area).

Referring once more to the figure, the lower-left corner shows three groups of temperature-strip photos, aligned just to the left of the front-side view of the cells they measured. Each group shows the same temperature strip photographed under the three different conditions. The three images were cropped and placed next to one another to make relative changes in color easier to see.

The top sensor in the "Cell 2" set indicates Bypass-mode ("**B**") backskin temperature with the cell 1/3rd shaded, the middle indicates FOZHS-mode ("**F**") backskin temperature with the same shade, and the bottom indicates its no-shade ("**N**") temperature at full-power production. Again, all three images came from the same temperature strip, at a fixed location on Cell 2.

Data for Cells 1 and 3 are shown as controls. These cells were left unshaded for all three modes.

Data for Cell 2 confirms that FOZHS mode protects shaded cells from overheating. In fact, the cell temperature was 1°C *lower* in FOZHS-shaded mode ("**F**" – note how the 60°C square on the temperature strip is dark) than it was for no-shade full power production mode ("**N**" – note the 60°C square on the strip is showing a color change). The Bypass-diode protection method, by contrast, caused severe heating, even in a visually defect-free cell. The 95°C square is brightly lit in the top ("**B**") photo of that same strip. (And, during that same test, we found the 130ºC hot spot with the pyrometer.)

Conclusion

Solar cell defects and failure modes can create extreme hazards, but only if the cells are subjected to reverse-bias voltages. The defects are completely benign in forward-bias conditions, due to the low power and current-density levels in the cells. Similarly, failure modes such as Zener and avalanche breakdown only occur in reverse-bias conditions, so defects which lower a silicon cell's breakdown voltage are not an issue as long as forward bias is maintained at all times. Solar panels with bypass-diode protection routinely subject cells to high reverse-bias voltages, dramatically elevating cell temperatures at best, and risking catastrophic failures and safety hazards at worst. Forward-Only, Zero Hot-Spot (FOZHS) technology from idealPV, however, continuously monitors string conductance and therefore the lowest conductance of any cell(s) in each string, keeping all cells in forward-bias state at all times. Eliminating reverse bias considerations from PV manufacturing systemically reduces costs from feedstock through finished panel. Without reverse bias to activate them, microcracks and other weathering effects are benign. FOZHS not only improves panel life by eliminating cell overheating; it enhances public safety.

http://idealpv.com/index.html