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Solar panel design factors to reduce the impact of cracked cells and the tendency for crack propagation

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***ABSTRACT* — Cracked cells represent a danger for high degradation rates of solar panels in the field. They also increase the sensitivity of system performance to shading events. This paper provides background on the origins of microcrack and crack generation, and outlines several approaches that can be taken at the wafer, cell, module and system levels to both reduce the occurrence of cracked cells in the first place, and to reduce their impact when they do occur. Outdoor IV testing under a variety of module shading conditions was performed to explore some of these approaches and to verify modeled results.**

1. Introduction

Most cracked cells within modules have their origin at the soldering (stringing) operation. The copper wires contract much more during post-soldering cooldown than the silicon, and the thermo-mechanical stress causes microcracks in the silicon beneath and adjacent to the silver busbars. It also causes cracks and discontinuities in the metallization. Softer copper wires with lower yield strength can yield more during cooling to reduce the stress, and such wires have been widely adopted. Solder with a lower melting temperature can reduce the stress, but the properties of such solder may be unattractive for other reasons such as brittleness, cost, and toxicity. Thinner wires will reduce the stress for multiple reasons, but this can increase resistive power losses. Stresses introduced during the lamination process can compound the problem.[1] [2]

Crack propagation within modules frequently has its origin in the asymmetric construction of most modules where a thick and stiff glass coversheet is present on the top side, and a thin and more pliant polymer backsheet is located behind the cells. When a module is bent concave down (e.g. – wind or snow pressing on the glass side), the cells are placed into tensile stress, and microcracks can propagate into full cracks.[1] The continuity of the metallization across these cracks is usually sufficient at first, but aging and mechanical load studies have shown accelerated degradation rates for modules with cracked cells as the continuity deteriorates and portions of the cells drop out of the circuit, as is shown in the Figure below from ISFH.[3]

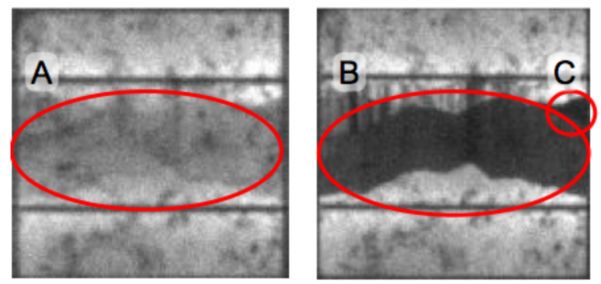

Fig. 1: Electroluminescence (EL) image of a cell with a crack a) before, and b) after humidity-freeze cycling. from ISFH[3].

Cells with such "open" cracks have reduced I_{sc} and I_{mp} values which puts them into a state similar to that of a partially shaded cell, where cell-to-cell mismatch losses occur and the cell can even be forced into reverse bias and dissipate power or force a bypass diode to engage with the loss of the entire string's power. Cells dissipating power in reverse bias represent dangers of hot spot heating and accelerated module degradation rates. Shading of these already hotspot-prone cells can significantly compound the problem. Bypass diodes have also been known to fail in the field, and thus, relying on them increases the risks for safety and module damage.

Much of the PV industry at the present appears to be accepting of the status quo. The literature is full of module EL images showing cracked cells, and justification of such defects by examples of relatively low efficiency degradation as these cracks propagate and open up, as is shown in the Figure below. Products across all industries tolerate some level of "defects" of various natures, and "over-engineering" the solar panels can result in a product that actually offers a higher levelized cost of electricity. The danger is in the statistics where some percentage of modules have significantly worse degradation and have increased sensitivity to module shading. A small number of well-publicized performance and safety problems could have a negative impact on the growth of the industry. Fortunately, a wide variety of cost-effective solutions exist for the cracking problem.

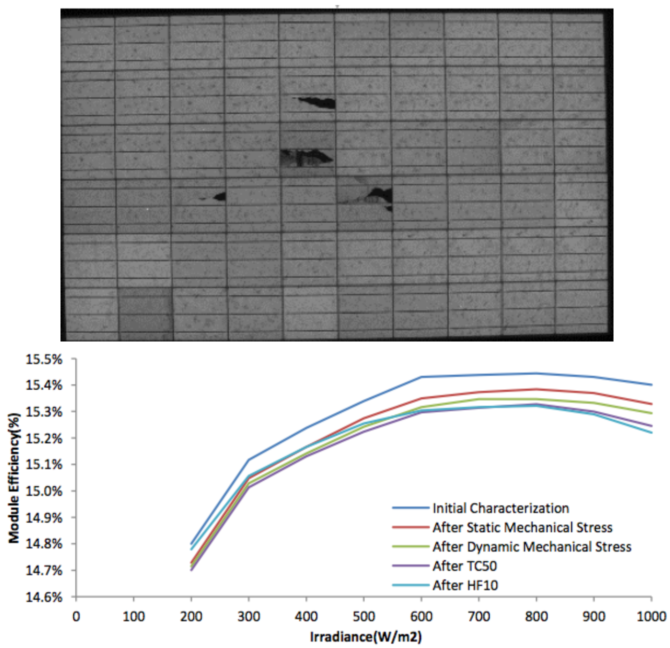

Fig. 2: . Electroluminescence image and efficiency vs. irradiance of a module after environmental testing - from Yingli.[4]

2. Solutions

Solutions to reduce the tendency for crack propagation and/or the impact of open cracks on module performance are found at the wafer, cell, module, and system levels. While some solutions are found with advanced cell architectures (e.g. – back contacted cells), we mainly restrict ourselves here to the commonly used architectures with busbars on both the front and back sides.

2.1. Wafer-level solutions

2.1.1. Thicker wafers

Microcracks are less likely to propagate in thicker wafers.[5] However, the path toward lower costs involves a further reduction in wafer thickness, so this is a poor solution. In fact, it is precisely the cell cracking problem that has stalled the industry in its efforts to reduce wafer thicknesses below 180 microns for the last several years. Thus, even though some of the solutions listed below may entail increased cost, these may be balanced by potential savings achieved by enabling future wafer thickness reductions.

2.2. Cell-level solutions

2.2.1. More busbars/interconnect-wires

The most common scenario in which an open crack causes a loss in effective cell area is one where the crack occurs beyond one of the outer busbars and the edge of the cell. In contrast, if a single open crack forms between two busbars, the redundancy in the wiring allows the current to still be collected, although at the expense of increased resistive power losses in the fingers. It is less likely to have 2 open cracks between busbars to allow the loss of effective area in these regions. The larger the number of wires/busbars, the smaller the area that can be completely lost at the edges of the cells, and the lower the resistive power losses when open cracks form between busbars. This solution has the potential downside of creating a larger number of open cracks per module due to the increase in the number of wires.

This solution is well underway within the industry with the past trend from 2 to 3 busbars and the present trend toward 4 or 5 busbars. The various wire array solutions using a larger number of round wires (SmartWire™ - Meyer Burger, MultiBusbar™ - Schmid, and Merlin™ - GT Advanced Technologies) offer a particularly elegant solution from a technical perspective, although their cost-performance benefits are less clear.

2.2.2. Wires placed closer to the cell edges

The most common approach in determining the positions of the busbars/wires is one where the resistive power losses in the fingers is minimized. This occurs where the finger length f between one of the outer busbars and the edge of the cell is roughly

$$f = (w - N \cdot b)/(2N), \quad (1)$$

where w is the cell width, N is the number of busbars, and b is the busbar width. The distance between any two busbars is roughly $2f$. Often, as the number of busbars increases, the width of each busbar (and wire) is reduced, so that we can assume the product $N \cdot b$ is roughly constant at ~ 4.5mm. With this assumption, we can calculate the maximum percentage of lost active area if an open crack occurs along the edge of one of the outer busbars as is shown below.

For a design with just 2 wires on a 156mm-wide cell, f is ~ ¼ of the cell width, and an open crack along this wire could result in a loss of ~25% of the cell current. For 5 wires, the loss is only ~ 10%, but the value of adding additional wires quickly diminishes regarding this concern.

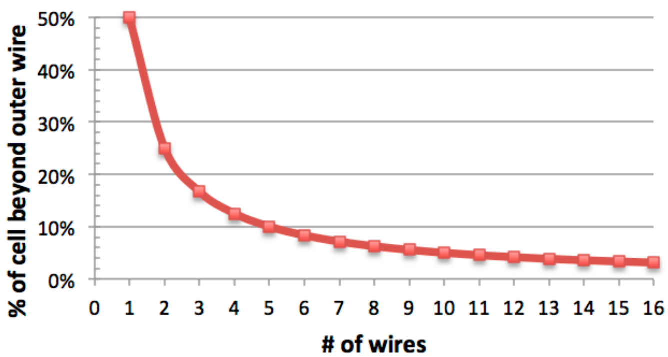

Fig. 3: Calculation of the worst-case scenario for cell area or current loss if an open crack occurs just outside one of the outermost wires as a function of the number of wires.

With the number of busbars now increasing within the industry beyond 3, we recommend placing the outer two busbars much closer to the cell edges (see Figure 4), since this will have a relatively small impact on resistive power losses in the fingers and could have a significant impact on module sensitivity to cracked cells. Should a crack occur outside the outer busbars, much less area will be lost.

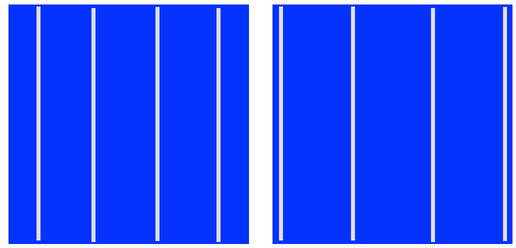

Fig. 4: 4-busbar cell with the conventional (left) and recommended (right) designs.

2.2.3. *Rectangular cells*

The wire thickness is generally chosen to minimize resistive power losses which are proportional to the third power of the busbar length. A recent trend in module design is to use half-size cells so that the length of the wires is cut roughly in half. With the peak current along the wires cut in two, one can significantly reduce the wire thickness without incurring significant resistive power losses. These thinner wires cause less stress in the silicon, and thus reduce the density of microcracks and the chances for crack propagation. Rectangular cells have the additional benefits of enabling more light harvesting from light reflected off regions around the perimeter of the cells, and a slight reduction in NOCT values. They have the downside of an additional processing step to cut the cell, a potentially weak edge where the cut occurs, lower throughput of the soldering equipment, and a slightly larger module size due to the increased number of gaps between cells and an associated increase in the related materials costs such as encapsulant, glass, and backsheet.

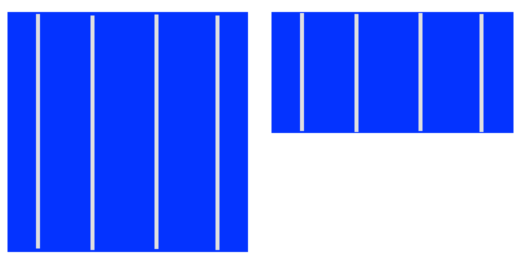

Fig. 5: Square cell and half-size cell designs.

2.2.4. *Optimized metallization pastes and metallization patterns*

As is often the case in the solar cell industry, the paste vendors are responsible for much of the progress in performance and costs. Improvements to the Ag and Al paste compositions, and to the geometries of the busbars[6], fingers, and rear Al/Ag overlap regions [7] have potential to reduce the severity of the cracking problem.

2.2.5. Cells with reverse "breakdown" at low voltages and uniform power dissipation

As was mentioned above, a shaded and/or cracked cell that is forced to operate at the current level of the rest of the string may be forced into reverse bias to "find" this current level. Rather than dissipating this power uniformly, most cells usually have localized shunts which means that the reverse current flows through small localized areas which heat up and can cause module damage (hot spots). Thus manufacturers often limit the cell current at a given reverse voltage (e.g. - <3A at -12V), and rely on bypass diodes to protect the cell, module, and array should the cell be forced far into reverse bias.

Reverse bias I-V characteristics vary widely among various wafer types, cell architectures, and even from cell to cell for a given technology. A variety of physical mechanisms are responsible for recombination that leads to increased currents in reverse bias.[8] A cell which enters "breakdown" mode at a relatively low reverse bias voltage would "fail" the common test at -12V, but actually may be superior in terms of module safety and performance. If the breakdown occurs at a low enough voltage, the product of current and voltage at the operating point may be low enough that only a fraction of the string's power is dissipated across the cell, and if this power is dissipated in a uniform fashion across the area of the cell, no damage may be done to the module. Examples of cell architectures that can exhibit such reverse bias characteristics include variations of the IBC design where there is a long length of abutted p-n regions such as the classic Sunpower design,[9] and the Zebra[10] and Mercury[11] designs. Figure 6 shows an example of the reverse bias characteristics of the Zebra cell.

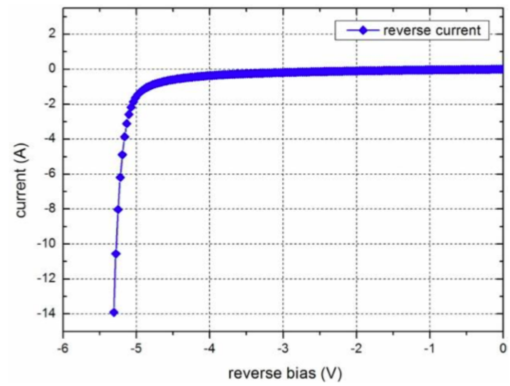

Fig. 6: Dark, reverse bias I-V curve of a Zebra IBC cell - from ISC-Konstanz[10].

In testing some old Evergreen Solar String Ribbon cells, we found a wide range of reverse breakdown characteristics, some of which occurred at quite low voltage (see Figure 7). In this case, thermal camera images showed the heating under reverse bias to be non-uniform but over generally larger areas than was seen for monocrystalline cells. This raises the question of whether non-standard wafer types could be engineered to possess favorable reverse bias characteristics in a more consistent and uniform manner.

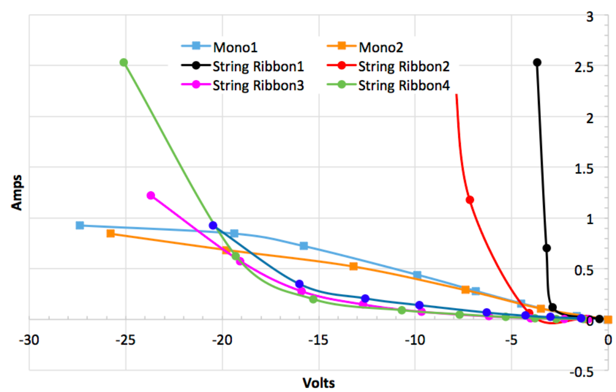

Fig. 7: Dark reverse bias characteristics of different cell types.

2.3. Module-level solutions

2.3.1. Optimized soldering materials, equipment and quality control

Most manufacturers have already migrated to very soft interconnect wires to reduce damage to the silicon, yet the industry uses a wide array of stringing equipment to solder these wires to the cells. Some equipment is more gentle than others, and proper setup and maintenance of the equipment is critical. Some companies still use operators to hand-solder wires, and acceptable quality control for this critical operation is near impossible when using hundreds of operators. Additionally, hand soldering involves a sequential operation of first soldering the front wires and then the back wires. Such an operation is inherently more damaging than the simultaneous soldering operation performed by stringing equipment.

While the emergence of electroluminescence (EL) testing has provided an incredibly valuable tool to aid in detecting open cracks following the stringing operation and during subsequent module processing, the reality is that cells can be heavily damaged by the soldering process, yet not develop visible cracks until after the module EL and IV testing. It is after the modules leave the factory and experience vibrations during shipment, and flexing during installation and snow/wind loads in the field that the majority of cracks will form. For this reason, the development of new measurement tools is needed to aid in process optimization and quality control. For example, in earlier work in soldering process and materials development at Evergreen Solar,[1] a breakage strength tester was used to quantify the soldering induced damage. Such a tester may provide complementary information beyond that given by more common wire pull strength tests.

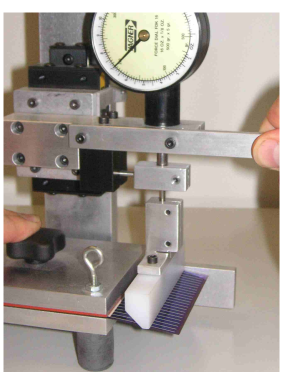

Fig. 8: Breakage strength tester utilized at Evergreen Solar for production quality control.[1]

Furthermore, one might consider it misleading for module manufacturers to proudly display module EL data to its customers showing crackfree modules, when modest bending of the modules of the type certainly seen in the field will cause cells to crack. A more forthcoming approach may be to subject the modules to some of these stresses in the factory prior to final EL and IV testing. The challenge here is that the initially closed cracks will usually have little impact on IV test results until they undergo long-term field exposure. In the future, it may be possible to develop factory tests to predict how the module will perform once these cracks open up.

2.3.2. Glass/glass module construction

Another recent industry trend is the adoption of glass backsheets. Such modules reduce crack propagation for two reasons. First, with a similar thickness and stiffness of material in front of and behind the cells, they are now located near the neutral plane such that bending the module in either direction is unlikely to place the cells under significant tensile stress, and thus the microcracks are unlikely to propagate. Secondly, depending on whether or not a frame is implemented, such modules may be stiffer overall and show less deflection for a given load. This design is not new, and old glass/glass modules built by Mobil-Solar/ASE/Schott and installed in challenging environments have shown extremely low degradation rates. Such modules also incorporated advanced ionomer encapsulant. Modern glass/glass modules using EVA encapsulant, while largely solving the crack propagation problem, must carefully address concerns related to acetic acid formation in this non-breathable design. If no water gets into the module, then acetic acid should not form, but 30 years is a long time, and some water may be present during module construction or find its way in through edges and wiring access points.

Similarly, other materials that add stiffness behind the cells (e.g. – Al foil/sheets), can also contribute toward increasing the symmetry of the panel construction. Such materials may also impart other benefits to the module as discussed next.

2.3.3. Backsheet materials that build compressive stress into the cells

If a backsheet material with a suitable CTE, stiffness, and thickness is chosen, the differential contraction during cooling from the lamination process may cause the cells to be "pre-loaded" into compressive stress. In this way, any subsequent bending of the modules that may otherwise have put the cells into tensile stress and caused crack propagation, will instead either just reduce the level of compressive stress or bring the cells to tensile stress levels that are lower than what would have occurred with conventional module designs. The Al backsheet utilized in TenKsolar modules is an example of such an approach.

While glass is close to an ideal coversheet material, one could also imagine a combination of coversheet and backsheet materials such that the usual asymmetry of stiffness is reversed and that snow or wind loads placed on the front side of the module actually place the cells into compressive stress. Since front side loads are more common than backside loads in the field, this approach may have some advantages.

2.3.4. Cells wired in parallel

If each cell in a module has a certain probability of developing a "problematic" crack, let us imagine that we divide each cell into two or more smaller cells that we wire in parallel. This can be accomplished by soldering wires from the top busbars of one cell to the top busbars of the adjacent cells in parallel before the wires extend to the backside of the next group of cells. In order to have the same lost area due to open cracks in the parallel-connected group, multiple problematic cracks would need to occur in the group. Since this is much less likely to occur than a single problematic crack in a full-size cell, the parallel-wired cell approach is much less likely to push cells into reverse bias power dissipation mode.

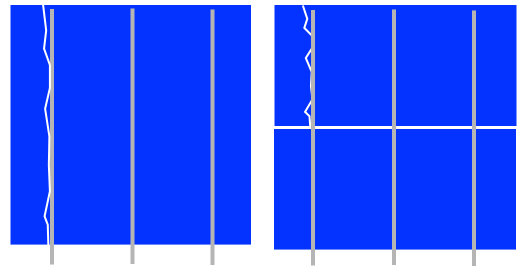

Fig. 9: A full cell with a crack, and two rectangular cells wired in parallel with one cracked cell.

An extreme example of such a design is the low-concentration architecture developed by Solaria where specially engineered glass focuses light on narrow slices of cells wired in parallel.[12] Parallel wiring of full-size cells has been adopted by TenKsolar to enable non-uniform illumination from its light harvesting system architecture as is shown below.[13]

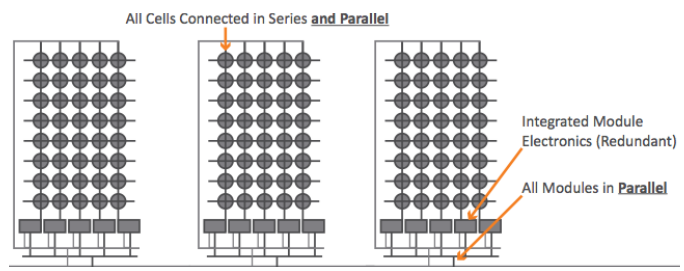

Fig. 10: Parallel cell wiring approach used by TenKsolar.[13]

2.3.5. Strings wired in parallel

The same logic that justifies cells wired in parallel applies to strings wired in parallel, although today's standard 60-cell or 72-cell modules generally place all cells in series.

To compare parallel vs series wiring we performed outdoor testing of an old Evergreen Solar panel (circa 1998) with 2 strings of 20 cells each. The panel allowed an easy change from series to parallel configuration of the strings with the change of jumper elements in the junction box. No bypass diodes were present in the junction box.

We performed IV measurements using a new, low-cost but high-accuracy, portable IV testing unit from PV Measurements. The module was measured outdoors under roughly 800 W/m^2 while one cell was shaded at varying levels in both parallel and series configurations. Shading of the cell roughly simulates the condition of having open cracks that cause the same percentage of lost area. All current values were normalized to the change in current of a separate reference cell, although the reference cell varied little under the blue-sky conditions. As can be seen in Figure 11, the parallel configuration performs better under shading. These old-generation String Ribbon cells have FF's that are far worse than those of modern day cells, and we would expect the difference between series and parallel configurations to be even greater for modules using cells with high FF's.

The same robustness of the parallel-wired design to cell shading applies similarly to robustness for cracked cells with lost area. The potential disadvantages of the parallel wiring approach are 1) more complicated wiring within the modules, and 2) higher resistive power losses and/or thicker and more expensive wires at both the module and system levels.

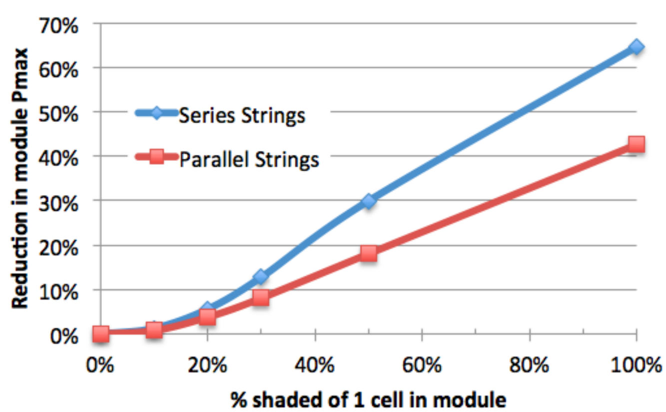

Fig. 11: Outdoor measured IV curves for a String Ribbon module at variable shading with strings in series and parallel wired modes.

We also examined the series/parallel vs cell shading/breakage issue by simulating module IV curves using the summation of individual cell IV curves with Microsoft Excel. We chose all cells to have identical IV curves except for the one shaded/broken cell. We used interpolation algorithms to enable the summing of IV curves at the same voltage values. A single diode model was used with an additional term to represent the reverse bias term, similar to the approach followed by PI-Berlin.[14] We examined two cases for the reverse bias characteristics since the power dissipation in the shaded/broken cell depends strongly on these characteristics. Figure 12 shows the IV curves for illuminated cells with both a high "breakdown" voltage and a low breakdown voltage that matches the IBC cell characteristics.

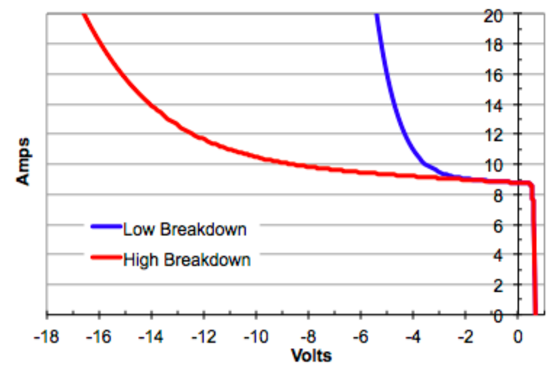

Fig. 12: Simulated IV curves for cells with high and low breakdown voltages that were used in the module simulations below.

Figure 13 shows the IV curves for a 60-cell module with no bypass diodes using 156mm cells where either all cells are connected in series or where two 30-cell strings are connected in parallel. The shading/lost-area of one cell in each module is varied from 0 to 100%. As can be seen, the low-breakdown condition helps tremendously when a large % of the cell is shaded or broken away. For more standard cells with high breakdown voltages, the parallel wired configuration is beneficial.

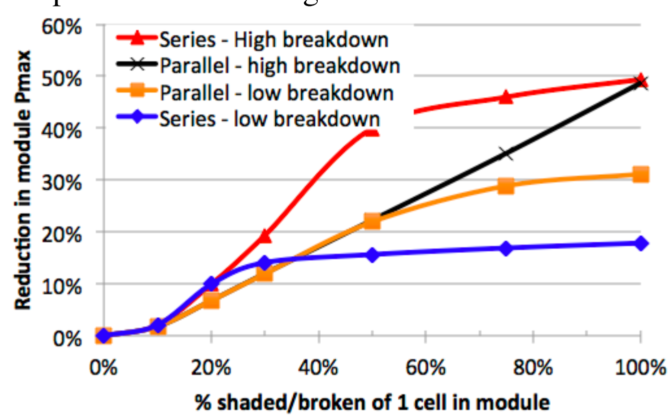

Fig. 13: Effect of broken-cell lost-area or shading of one cell in a 60-cell module with either all cells wired in series, or for 2 parallel strings.

2.3.6. Stiffer modules

Increasing the stiffness of modules will reduce the amount of deflection for a given front-side load, thus reducing the tensile stress levels and cracking within the modules. A wide variety of approaches can be pursued to make stiffer modules:

- Thicker front glass.
- Glass backsheets instead of polymer. See section 2.3.2.
- Alternative encapsulants with higher modulus values (e.g. – Ionomer). Such encapsulants may be more expensive, and the impact of alternative encapsulants with different modulus values and glass transition points on interconnect wire fatigue must be considered. Also, there is some concern that stiffer encapsulants or encapsulants with higher glass transition temperatures may contribute to increased cracking in the field.[15]
- Sturdier frames and/or frames with additional stiffening elements such as crossbars. This increases materials and shipping costs. However, the costs should be examined at a system level since clever engineering can increase module costs but reduce racking/installation costs and vice versa.

2.3.7. Electrically conductive adhesives, composites, and films

Since the primary formation mechanism for microcrack formation is related to the soldering operation, replacing solder with more flexible materials that "harden" at lower temperatures and that impart less stress on the silicon should largely solve the problem. However the PV industry is justifiable conservative when it comes to changing a design that has served it well for many decades. The primary materials being considered as replacements include silver-filled conductive adhesives, composite materials containing a mixture of a polymer based and particles of solder, and tape materials with conductive particles embedded in an adhesive coating.

2.3.7.1. Silver-filled conductive adhesives

While these materials cost more than the solder coating on standard interconnect wires, one can potentially eliminate the busbar silver in the cell, and contact the fingers directly with this approach to offset these costs. The main risk with this approach is degradation (increase) of the contact resistance over time between the conductive adhesive and the wire. Multiple industries have shown excellent stability when contacting silver surfaces with these conductive adhesives, and thus good prospects exist for contacting interconnect wire with a thin coating of silver. Unfortunately, a silver coating adds cost to the wire, and the more desirable approach would be to contact a low-cost tin-coated wire surface. However, galvanic corrosion over time at a Sn-Ag interface, even with advanced stabilization packages, makes this a highly risky approach. A better approach may be to skip metal coatings entirely, and to contact the Cu wire surface directly although some organic protection layers may be desired to reduce discoloration, depending on the encapsulant used. Recent work at ISC-Konstanz looks quite promising on Ag-coated or bare Cu wires.[16]

Finally, while many industries deal successfully with such dispensed materials, the maintenance and downtime at the stringer associated with these "messy" materials could be a barrier for some companies. Screen printing is also a possibility for application of these materials.

2.3.7.2. Composite polymer/solder materials

These interesting materials contain a mixture of low-temperature solder particles in a thermoset resin. For example, Hitachi Chemical sells the products CP-300 and CP-450. The polymer component will presumably deform during cooling from the solder melting point to take up the differential contraction between the copper wires and the silicon, and thus eliminate microcracking within the silicon. The differential contraction between the wire and the silicon is less when solders are used with lower melting points, and while such solders are often brittle, the polymer component may reduce concerns related to fracturing of such solders. The resin base can also help ensure good adhesion strengths. Unfortunately, there is very little in the literature concerning the performance of these materials.

2.3.7.3. Films with conductive particles

These materials are sold by companies such as Dexerials and Hitachi Chemicals. Their primary application is within the flat panel display industry, although it appears likely that Panasonic has used this approach for connecting its HIT cells. These tapes have a release liner that requires disposal, and the materials costs are likely higher than those for conductive adhesives. However, these materials are inherently "non-messy" and so stringer uptime should be high. Most importantly, their possible track record at Panasonic/Sanyo adds to the confidence concerning module durability. Recent work again at ISC Konstanz[17] looks promising in terms of module stability, at least for designs with front busbars, and potentially for lower-cost designs where the conductive films contact the fingers directly.

2.3.8. Increased number of bypass diodes

Some groups are looking at increasing the number of bypass diodes in the modules to protect against shading and damaged cells.[18] In this way, one doesn't lose a third or more of the panel output when a problem occurs.

2.4. System-level solutions

2.4.1. Module level electronics

Implementing maximum power point trackers, microinverters, and charge controllers at the module level is another industry trend that may help when it comes to low performing modules with cracked cells. In this way, the low performing modules may have less of an impact on the performance of the whole string of modules.

2.4.2. Racking that reduces module bending

This is related to the stiffening of modules topic, and as mentioned above, the module laminate, module frame, and racking need to be considered together as a unified system. Most designs merely support the modules at 4 points near the edges. Cost effective designs to reduce module bending may be best implemented during module installation in the field.

3. Conclusions

We have outlined a wide variety of solutions to the cracked cell problem. The table below summarizes these solutions into categories of whether they act as a cure to fundamentally reduce the formation/propagation of cracks or whether they act more as a bandaid to reduce the impact of the cracks. We have also subjectively ranked them according to their desirability taking into account various risk, cost, and factory disruption factors.

Table 1. Ranking of solutions discussed in this paper.

Method	Cure/ Bandaid	Desir-ability
Optimize soldering and QC	Cure	High
Improved metallization	Cure	High
Racking to reduce bending	Cure	High
Glass/glass construction	Cure	High
Stiffer modules	Cure	High
Compressive stress from backsheets	Cure	High
Conductive adhesives	Cure	High
More wires	Bandaid	High
Wires closer to edges	Bandaid	High
Low reverse breakdown	Bandaid	High
Strings wired in parallel	Bandaid	Med
Cells wired in parallel	Bandaid	Med
Rectangular cells + thin wires	Cure	Med
Module level electronics	Bandaid	Med
Increased bypass diodes	Bandaid	Med
Thicker wafers	Cure	Low

It is our assumption that a growing number of manufacturers will fundamentally solve the cracking problem, giving them a marketing advantage over their competitors who ignore the problem. A few years from now, we may look back in disbelief at the fractured EL images that are presently considered acceptable.

We have also demonstrated the usefulness of an outdoor module IV measurement system with high accuracy that is an order of magnitude less expensive than an indoor system with a light source. Enabling more researchers to perform experiments on module performance will benefit the industry. Also, since crack propagation and crack opening generally happens after the modules leave the factory, field testing of individual modules with such equipment can provide valuable information on module degradation rates.

4. *Acknowledgements*

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