<u>Solar Cell Microcracks Are Inevitable, And idealPV FOZHS Makes Them Irrelevant</u>

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Solar cell microcracking is inevitable, but crack induced catastrophic failure doesn't have to be.

Most crystalline solar cells have cracks, or will develop them over time. This is not a flaw; it is the inevitable result of making a sheet of silicon that is more than 700 times wider than it is thick, and then putting it outdoors for 20 to 30 years. An environment of baking sun, bitter cold, heavy snow, pelting hail, buffeting wind and falling pinecones will mechanically and chemically stress anything.

Add to this the daily thermal cycle, which contracts, expands and flexes metal contacts, solder and wire interconnects. It is no wonder that microcracks will develop even in cells that were originally free of defects, simply because they were subjected to standard mechanical test procedures.

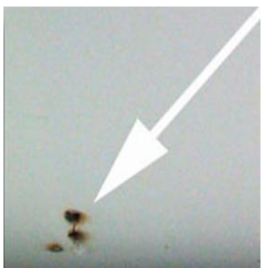


Fig. 2: Pinhole burns through the backskin of a solar module

When one combines microcracks with normal solar power levels and traditional maximum power point tracking (MPPT), catastrophic breakdowns can result. Localized hot spots can burn through silicon at over 2,577°F (Fig. 1). Other failures include front glass cracks, crack shadows, worm tracks, snail trails, front or back bubble delaminations (Fig. 2), dead cell sections, internal arcs at over 14,000°F and, worst of all, uncontained fires (Fig. 3).

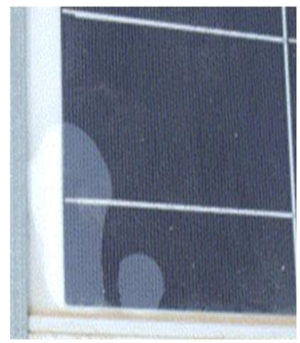


Fig. 1: Bubble delamination

It has been shown that microcracks, by themselves, have little effect on electrical power production. This is because a microcrack is typically only a few microns wide, more than 10 times narrower than smallest metal finger in the web of interconnecting metal attached to both sides of the solar cell. This web of ductile metal keeps all areas of the brittle silicon cell connected together. Even if there is a crack that separates one part of the silicon from another, all a microcrack can do by itself is separate one large solar cell into two or more smaller ones, each connected in parallel. Since the total area is the same, all the parallel photocurrents will add up to the original value, and total power production remains unchanged. Köntges et. al. have shown that *artificially initiated microcracks in the silicon wafer do not reduce the power generation of a PV module by more than 2.5% if the crack does not harm the electrical contact between the cell fragments* [4].

Fig. 3: White hot silicon, aluminum, copper and silver escape a solar module

Solar power has been subject to a conceptual flaw rooted in the idea that cracks do not exist, or will never exist. This faulty assumption causes good cells to be discarded on the production line and allows a solar electric generating station to drive power into all kinds of faults, triggered by cracks that inevitably form in the field, including dangerous and uncontained faults that propagate destruction beyond the cell and solar module itself.

Most cells contain microcracks in the manufacturing process. "Inspection will concentrate on identifying those microcracks that are deemed critical," explains Guido Eberhart, sales manager at Isra Vision in Darmstadt, Germany [1]. *Crack propagation can be accelerated if the cell undergoes bowing or flexing. These are common problems related to the mismatch of thermal expansion coefficients between the Si layer and the Al back contact layer. As a consequence, cell bowing can occur during the contact firing fabrication process as well as during operation, because solar cells are subjected to large diurnal-nocturnal thermal variations* [2]. *The generation of large thermal stresses within the solar cell can also promote crack branching and even propagation through the Al–Si eutectic layer, generating a through-crack* [3].

A mechanical load test complying with the requirements of IEC 61215 10.16 is used as a standardized way to insert microcracks in the solar cells within PV modules. The test is performed using a high pressure snow load option. The mounting during the mechanical load test is varied for the different modules in order to systematically introduce significantly different numbers of microcracks into the module cells. To stress the microcracks caused by the mechanical load test, an accelerated aging is performed by a humidity freeze test according to IEC 61215 10.12, with a reduced humid time of 6 h and 200 cycles. The sequential combination of the two tests is effective for cell crack initiation and propagation, as well as subsequent electrical interruption of the metallization grid. This testing sequence represents a hostile climate with large temperature fluctuations combined with heavy snow load on the PV modules [4].

Microcracks are benign when a solar cell is producing power. When a cell converts light to electricity, photons raise electrons to a higher energy state. These electrons are harvested by metal contacts, and sent off through wires to an electrical load where they do work. Since energy is transferred out of the cell to perform useful work, the temperature of the solar cell is actually reduced.

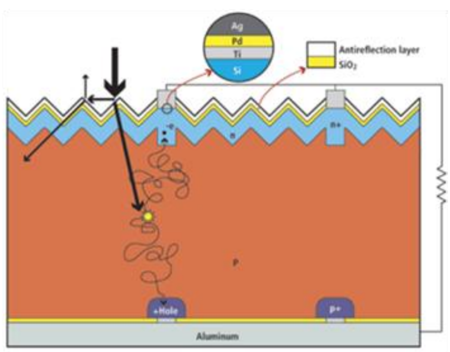


Fig. 4: Normally, a photon enters from the top and energizes an electron

A solar cell in production is forward biased with its potential at or slightly below the band gap of its junction (about +0.5V for silicon). In this mode, the electrons flow forward through the cell's junction in the form of photocurrent (Fig. 4). After the electrons do their work elsewhere by giving up their +0.5V, they return to the junction to be re-energized when another photon is absorbed. In forward mode, holes and electrons are in contact; there is no depletion zone, and the electric field is relatively small.

Microcracks cause problems when a cell is reverse biased and is consuming power. With the cell's junction reverse biased, electrons and holes move away from one another, forming a depletion zone (orange, Fig. 5). As the reverse voltage increases, this gap gets wider and the charge on the electrons on one side gets larger; the strength of the electric field across the depletion zone increases, and the potential for a failure is created. The first two ingredients for a hotspot are present: partial shade and reverse bias. Now all that is needed is a trigger to start the reverse flow of current. *Hotspot heating occurs in a photovoltaic (PV) module when its operating current exceeds the short-circuit current of a shadowed or faulty cell in a cell-string. The heating can become high enough to become a fire or electrical hazard* [5],[6].

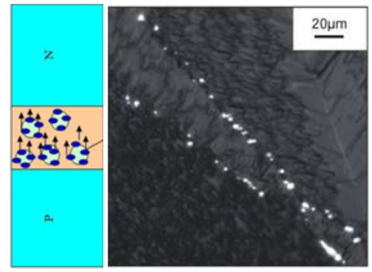


Fig. 5: When reverse biased, electrons are forced out of their bonds and emit photons and heat

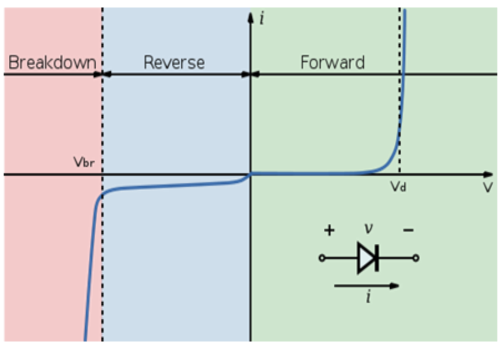


Fig. 6: Avalanche breakdown in red

As the voltage across a cell is swept negative, the current increases rapidly, and a failure occurs (Fig. 6). This mechanism is known by several names: nonlinear shunt, avalanche breakdown, hot electron breakdown, dark current breakdown, or low reverse breakdown voltage (BV). This type of breakdown has a positive temperature coefficient, which means the trigger voltage becomes smaller as temperature falls. Unfortunately, silicon solar cell voltage becomes larger with falling temperature, worsening the effect.

This is where the crack does its real damage: by acting as a trigger to a tiny, intensely hot spot. A crack propagates through the surface of a cell and into the conductive, phosphorus or boron doped silicon. Because the cross section of a crack is "V" shaped, it not only brings surface electrons closer to the junction, it concentrates their electric field. The cell shown in Fig. 7 is 170 microns thick. The amorphous layer shown in the left of this Scanning Electron Micrograph (SEM) image is a metal contact 30 microns thick.

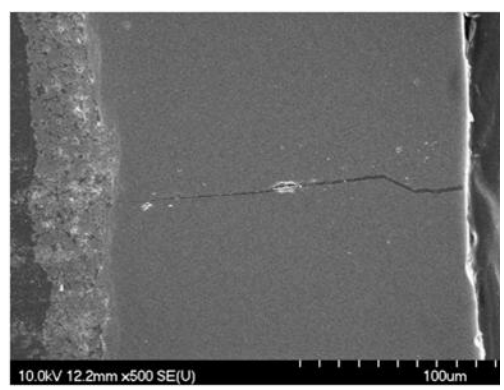


Fig. 7: Cross section of a 2 micron wide microcrack in a crystalline solar cell.

As the negative bias on the cell increases, somewhere along the crack the field intensity will cause an electron to shoot trough the depletion zone, accelerated by the highly localized and intense electric field.

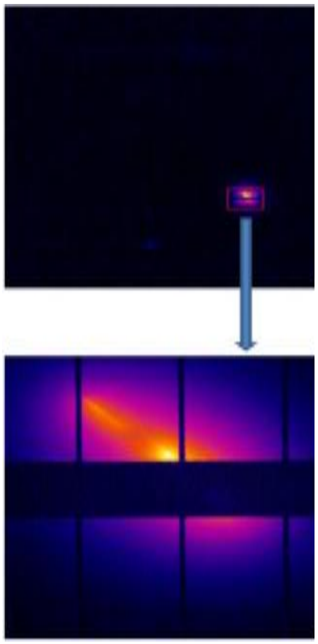


Fig. 8Thermal image of a microcrack partially under a metal contact

This hot electron flow is a very high current in a very tiny space. The highly charged electrons physically damage the atomic structure of the junction, and the high current density causes very high temperatures focused on one tiny point.

At these temperatures, the boron and phosphorus in the cell become fluid, diffusing into one another, and creating an ohmic short (where current is proportional to voltage). This produces temperatures exceeding 2,577°F, where silicon melts.

At 392°F, the ethylene vinyl acetate (EVA) between the front glass and the cell surface melts and delaminates. The molten silicon then punches a pinhole through the cell, the EVA and the back sheet, or rear panel cover (Fig. 8). When this happens, it escapes the module completely and proceeds through anything immediately below the panel. Dry vegetation, bird's nests, insect colonies and other materials commonly found under solar panels may spontaneously ignite well below 2,577°F.

A major technical issue in testing [IEC 61215 and UL 1703] is how to identify the highest and lowest shunt resistance cells under reverse bias, and then how to determine the worst case shadowing for those cells, which are the cases that produce the highest local temperature. The purpose of those tests is to detect cells that have significant reverse bias defects [6].

Currently, there are three different test methods used in the industry to identify and address this issue. These three methods are based on the UL 1703 (intrusive) standard, the ASTM E2481-06 (non-intrusive) standard and the IEC 61215 (non-intrusive) standard. All three standards begin with identification of the cells with the most significant reverse bias defects; therefore, any sample deliberately submitted with such a defect will fail ASTM and IEC, and will fail UL if randomly selected [5].

To identify the low, median and high shunt resistance cells, the UL 1703 standard calls for a good cell screening method on a small set of randomly selected cells; typically, the sample size is 10, which results in a high likelihood of not selecting the worst cells. Also, this method requires the construction of a special test module, and the periodic testing of production modules is not practical [5]. *In some cases, a cell identified and reversed biased into failure by UL 1703 was not deselected by ASTM methods. The reason for the absence of hot spot failure detection in the ASTM method, but the presence of hot spot failure detection in the UL method, could be potentially attributed to the presence of the bypass diode in the test module used in the ASTM method, which bypasses the current and partly shares the heat dissipated in the cell* [5].

The good news is that the melt may effectively open the short and stop conductance. The bad news is that we now have a solar panel with a hole in it, exposing anything near the hole to as much as 1,000 VDC and the panel to water, insects, vegetation, contaminants, etc.

When a section of the microcrack melts through, it can propagate further breakdown sites along the microcrack, allowing more conduction and melting. This progression of the hotspot along a microcrack forms a trail of delaminated EVA between the front of the cell and back of the front glass. Operators and installers see this often enough that they variously describe it as a “worm track” or “snail trail” (Fig. 9). Since it is rarely possible to see the actual microcrack without special equipment, solar manufacturers often call these “crack shadows”. The thermal shocks of the successive melts can also help propagate the crack.

Fig. 9: Microcrack shadows

The initial width of a microcrack is quite small. At 1 or 2 microns, they are small enough that they cannot propagate through even a small metal contact. Were it not for the temperatures associated with reverse conduction through the microcrack, the metal would remain intact and the microcrack would not affect solar energy production.

Electroluminescence (EL) has been found useful in the detection of solar cell defects. Solar cells under EL show characteristic luminescence effects that lie exclusively on the defects, and in particular on the grain boundaries contained in the multicrystalline material. Optical radiation through the transition of electrons to a low-energy ground level state produces very sharp images.

"This makes it possible to locate and identify defects with a spatial resolution previously not known or achieved," says Marius Grundmann, Director of the Institute of Experimental Physics and head of the Department of Semiconductor Physics, who supervises the research together with Kai Petter of Q-Cells SE. The method established by the researchers is called ReBEL, which stands for "Reverse Bias Electroluminescence" [7].

Fig. 10a: Can you see the microcrack in this new cell?

A new, never reverse biased cell seen optically shows no obvious microcrack (Fig. 10a). The same cell under Electroluminescence shows a clearly visible microcrack (Fig. 10b); the entire cell continues to emit light, indicating that its power production is intact.

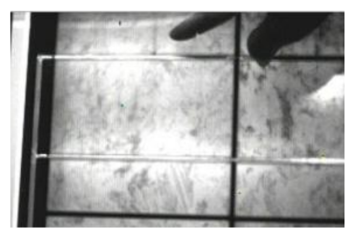
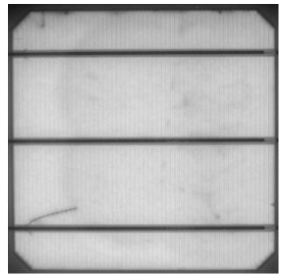


Fig. 10b: This crack has no effect on energy production.

Fig. 11: Chinup Technology Co EL-CT01A



Microcracks do not normally cause a power loss, and thus cannot be detected on a flash tester. Several pieces of specially built EL or IR thermography equipment must be inserted into several points in the solar manufacturing process to detect them. The purpose of this equipment is to reject wafers, cells, strings or even entire solar panels. None of this is necessary using idealPV technology.

Prior to idealPV's FOZHS (Forward Only, Zero Hot Spot) technology, microcracks were a serious problem in solar panel operation. Since a microcrack can be introduced at any stage of the manufacturing process, considerable equipment cost, production time and material waste has been expended in a attempt to keep microcracks out of solar panels. This approach has been proven futile since microcracks may form at any time even after manufacturing is complete, even decades later.

In the past, microcracks were seen as preventable "manufacturing defects" that did not form post sale. Under the belief that a solar panel without a microcrack would never form one, solar panel safety standards and test procedures have not required that solar panels contain microcracks when they were tested and certified as safe.

Since it is well known that solar cells containing a reverse bias defect are likely to catastrophically fail safety testing, manufacturers do not intentionally submit samples that contain microcracks. In related reasoning, certification tests that may result in the formation of new microcracks are not intentionally performed before hot spot testing.

As a result, the solar panels in figures 1, 2, 3 and 9 are post sale, latent failures of production units which were believed to be safe when they were installed. Figures 1, 2 and 9 are of commercially deployed solar panels in the field. Although Figure 3 was an induced failure in a laboratory, the solar panel was commercially available and the failure was typical.

Legacy Maximum Power Point (MPP) or Hot Spot Suppression (HSS) techniques were designed based on the notion that there is a safe reverse bias level guaranteed for decades by the solar cell manufacturer. Under this assumption, a limited amount of reverse bias will not cause a local hot spot to form.

When a cell in a solar panel is soiled or partially shaded, the solar power station's Mpp controller, seeking higher current, forces the low production cell into being reverse biased by the other power producing cells in the panel. The notion of a minimum safe reverse bias allows this cell to remain in this condition, allowing for higher currents and power to be delivered by the remaining cells via bypass diodes.

However, as we've seen, there is no guaranteed minimum safe reverse bias once microcracks have formed. And they will form as a natural part of the weathering and aging process. The shaded cell, instead of standing up against the reverse-bias voltage and blocking (almost all) the current flow, breaks down, and current shoots upward. The maximum power point controller detects more current available, but has no way of knowing it is at the expense of the shaded cell being damaged. So it continues at an operation point which virtually guarantees that damage to the cell and panel will progress or worsen.

FOZHS does not permit reverse bias, rendering microcracks unimportant to the manufacture, installation, use or weathering of solar panels. The onboard intelligent power converter uses physics and math to present an idealized current and voltage (IV) curve to standard inverter equipment. It also produces a decoupled ideal IV operating point to the solar cells. idealPV solar panels are built with a unique substring panel architecture which improves partial shade performance without requiring reverse bias of the cells or the use of bypass diodes.

Fig. 12: 34¢/Wdc in low volume for "rejected" cells

FOZHS makes community assembly of solar programs possible by removing the inherent risks, manufacturing complexities and costs associated with reverse breakdown.

Fig. 13: An idealPV solar panel is assembled from low cost, low reverse breakdown solar cells.

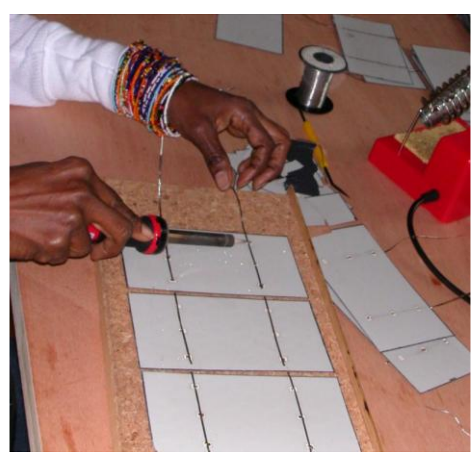


Fig. 14: A volunteer solders tabbing wire to a solar cell for a community project.

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